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AUDITORY EVOKED POTENTIALS AS A FUNCTION OF SLEEP DEPRIVATION AND RECOVERY SLEEP

Final Report

September 29, 1985

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Bowling Green, Ohio 43403

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Four questions were addressed by the present research: They relate to the effects of:

a) 48-hours of sleep deprivation on endogenous event related potentials (ERPs); b) circadian rhythms on ERP recordings; c) different durations of recovery sleep (1, 2, 4 hours) on ERPs. A central question asked was: Can ERP changes associated with sleep loss predict the performances changes associated with sleep loss? i.e. can changes in ERP recordings be used to predict performance degradation associated with sleep loss? Forty male subjects (30 deprived of 48-hours of sleep, 10 control (nondeprived) subjects were participants. Every four hours (12 four-hour blocks) subjects were tested on performance batteries
including the PAB) and had ERPs recorded (P1, N1, P2, N2, P3). The major findings of the study were: decreases in amplitude for N2, P3 and N2P3 across the reprivation period; a circadian rhythm was apparent for both ERP recordings and performance; performance degra-

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dation on virtually all tasks was apparent across the 48-hour deprivation period; naps of 1-hour were not restorative but may be counterproductive as indexed by ERP amplitudes and performance measures; naps of 2 and 4 hours were only partially restorative; a high correlation obtained between performance and ERPs across the 12 four-hour blocks; a high correlation obtained within a block between ERP values and performance; N2 may be a better predictor of performance that P3. The results suggest overall that certain ERP measures may be useful in identifying sleepiness/alertness and in predicting performance levels.

PROJECT SUMMARY

This research studied changes in event-related brain potentials (ERPs) in sleep-deprived subjects over a 48-hr test period. The questions addressed were: 1) What are the effects of different durations of continuous wakefulness on the various components of cortical evoked response potentials (ERPs)? 2) How do circadian rhythms affect ERPS under conditions of sleep deprivation? 3) How do different amounts of recovery sleep affect ERPS? 4) Can deprivation-related changes in ERPS be used to predict changes in tasks involving psychological functioning and psychomotor performance?

Forty subjects participated in the study and were randomly assigned to four groups (three sleep deprived experimental groups and one non-sleep deprived control group). For each participant, ERPs and a variety of performance measures were assessed in four hour blocks (12 Blocks) for 48 hours. Measures were taken at the same times from control subjects except during designated sleep periods. At the end of the 48-hr test period, the experimental subjects were allowed recovery sleep of either 1, 2, or 4 hours and ERP and performance measures were again recorded.

Marked performance degradation was found in association with sleep deprivation and circadian rhythms, thus replicating earlier research. Some tasks showed greater degradation than others. Evoked potentials also showed systematic changes over the experimental test period in association with sleep deprivation, and circadian rhythms. Some effects of repeated testing were also observed but the effects were not pronounced. Recovery sleep of 1, 2, or 4 hrs was not sufficient to return performance or evoked potentials to baseline values, although 4-hrs of recovery sleep was superior to 1 or 2 hrs. There was some correspondence between evoked potentials and performance. Analysis of this correspondence revealed that some performance measures covaried with certain components of the evoked potential across the 12 test blocks of the experiment. Correspondence was also found between certain evoked response components and performance within test blocks. The results appear promising in terms of the predictive value of certain ERP components. We note the need for further research to replicate and extend the predictive relationship between evoked potentials and performance under adverse environmental conditions.

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FOREWORD

This document is a draft of a final report for Bowling Green State University and University of Southern Mississippi's contract with the U. S. Army Medical Research and Development Command (USAMRDC) (DAMD17-84-C-4084). In an addendum is presented a preliminary report for Contract Modification #1 of this same contract. (Modification No. P50001)

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1.0 INTRODUCTION

1.1 The Problem

Increases in technological sophistication in civilian and military work settings has resulted in great demands being placed upon human operators of man-machine systems. Machines which can respond more quickly and which can perform a greater number of functions require that operators increase their readiness to respond and be able to respond at a constant and high level of readiness to a greater variety of situations. This situation has resulted in a greater need to understand the factors which limit the performance of human operators and a greater need to be able to monitor the performance readiness of operators; particularly under conditions that might reduce readiness (e.g. sleep loss, fatigue, boredom, hypothermia, hyperthermia, exposure to chemical agents, etc.).

In the past, researchers have used a variety of measures to infer central states related to performance readiness such as alertness, sleepiness, boredom, etc. The measures used include physiological measures such as blood and urine composition, heart rate, electromyograph (EMG), and others. Inferences based on these measures, however, have been of limited value in helping to predict and understand performance. One likely reason for the lack of success is that these measures deal with peripheral physiological systems which are too distant from central processes to permit valid inferences. The research proposed here assesses the usefulness of event-related brain potentials (ERPS) which are considered by some to be more closely related to central processes.

Event-related potentials are brain potentials which are measurable using scalp electrodes and which are thought to be determined by both the physical and psychological characteristics of stimuli. Recent technological developments have resulted in reliable and efficient procedures for recording, measuring and quantifying this activity. Because ERPs have been found to be related to performance on tasks involving stimulus detection (e.g. Ruchkin and Sutton, 1973), discrimination (e.g., Poon et al., 1976), decision making (Hillyard et al., 1971) and because they are thought to provide neurophysiological correlates of central states such as attention (see Callaway, 1975) and central processes such as information processing (e.g., Donchin et al., 1973) and allocation of processing resources (see Wickens et al., 1977), hundreds, if not thousands, of studies have been conducted on the relationship between ERPS and human performance.

The present research is a study of the possibility that ERPs will provide a reliable, valid, and practical way of inferring central processes related to performance while assessing the effects of environmental, task, and field conditions. As a first step in our approach to this complex problem, we focus on identifying fundamental relationships that may exist between ERP measures, different levels of sleep deprivation, and performance on several tasks involving psychological functioning and psychomotor performance. Sleep deprivation was chosen as a laboratory manipulation because 1) of the extensive research on the topic; 2) it is an important, yet simple variable to quantify and to vary systematically; and 3) of its high inherent interest in military and civilian work settings.

1.2 Sleep Loss and Performance

Research on the effect of sleep loss on performance has been extensive (Johnson et al., 1981; Webb, 1982) The following relationships have been documented (cf. Johnson and Naitoh, 1974): 1) The more difficult and/or complex the task, the more sensitive it is to the effects of sleep loss; 2) newly acquired responses, especially if they are skills, are more sensitive to sleep loss than are well established ones; 3) longer, less interesting tasks are more sensitive to sleep loss than shorter, more interesting tasks ; 4) externally-paced tasks are more sensitive to sleep loss than are self-paced tasks; 5) tasks without feedback are more sensitive to sleep loss than tasks with feedback; 6) tasks involving short term memory, sequencing, and/or information processing are sensitive to sleep loss; 7) the effects of circadian rhythms are exacerbated by sleep loss -- the longer the period of deprivation, the more pronounced the circadian rhythm factors; and 8) the effects of sleep loss are attenuated by high levels of motivation.

It is clear from the above that progress is being made in identifying the effects of sleep loss on performance. Also, there is a growing understanding of the characteristics of performance tasks which make them differentially vulnerable to sleep-loss effects. Progress has been slow, however in understanding the physiological mechanisms underlying these performance changes. Peripheral physiological measures have been found to correlate with degradation of performance on some tasks, however, the relationships have not, in general, been found to be strong or to generalize across different types of tasks (see Kahneman, 1973 for a more detailed analysis). The absence of readily obtainable and generally useful information about sleep-loss effects on specific physiological mechanisms has resulted in researchers relying more heavily on measures of the major symptom of sleep loss, i.e., sleepiness.

1.2.1 Measures of Sleepiness

One method of measuring sleepiness involves monitoring ongoing electroencephalographic (EEG) activity. EEG activity changes with wakefulness, drowsiness and sleep and investigators have found a relationship between performance and EEG indicators of alertness, drowsiness, and sleep (e.g., Gale, 1977; O'Hanlon and Beatty, 1977). This measure then may be very useful for monitoring performance readiness. A limitation of the ongoing EEG as an indicator of sleepiness, however, is that it may be a correlate only of the earliest stage of sleep onset and may be useful only in those situations where sleepiness is so great that sleep onset itself begins to intrude in the peformance setting. That is, it may be useful only at the very low end of the arousal continuum.

Other measures of assessing sleepiness also have problems. Subjective ratings of sleepiness such as the Stanford Sleepiness Scale (Hoddes et al., 1973) have proven to be surprisingly useful in a variety of situations, but is limited as a general purpose research tool because of concerns about subject differences in perception of sleepiness, limited sensitivity, subject response sets, the ease with which responses can be faked, etc. Recently the Multiple Sleep Latency Test (MSLT; Carskadon and Dement, 1979), which is based on the time to sleep onset in a series of brief naps, has been introduced. It is probably the most widely accepted measure of sleepiness. While the MSLT is an improvement over other measures of sleepiness, it too has problems: 1) It is cumbersome, costly, and time consuming and must be done in a sleep laboratory with standard polygraphic leads attached; and 2) "floor effects" are apparent since with increases in sleepiness the range of values available to detect the sleepiness is very limited. Obviously, identifying more convenient and sensitive measures which correlate highly with sleepiness would be useful. There is some evidence to suggest that ERPs are correlated with sleepiness in humans. This evidence is reviewed below.

1.2.2 ERPs, Sleep, and Sleepiness

There is evidence to suggest that ERPs may be an index of the sleep/wake continuum. Williams et al. (1962) recorded ERPs to clicks under different levels of alertness (waking and different sleep stages) while also monitoring EEG waves. They found that as the subjects went from waking to slow wave sleep, the characteristics of the ERPs also changed. With non-rapid-eye-movement (NREM) sleep, the amplitude of certain components of the ERPs (P1 and N2) increased while the amplitude of other components (N1 and P2) decreased. In rapid-eye-movement (REM) sleep, all amplitudes decreased. Similar findings were reported by Weitzman and Kremen (1965), who also reported increases in latency of the components from wakefulness through sleep stages 1 through 4 (NREM sleep). Further evidence of these relationships was provided by Hakinnen and Fruhstorfer (1967) and Fruhstorfer and Bergstrom (1969). These investigators additionally found that N1 and P2 amplitudes decreased in the presence of theta waves (4-7 Hz; presumed drowsiness).

More recently, Broughton et al. (1982) assessed ERPs in medication-free narcoleptic patients and in normals. Without medication, narcoleptic patients experience sleepiness throughout the day. It was found that the groups differed on latency of the component N0 (shorter latencies for the narcoleptics) and a decrease in amplitude of N1, P2, and N2 in the narcoleptic group. An interesting and particularly significant finding was that changes in the auditory ERP occurred while the ongoing EEG was that of wakefulness. This suggests that evoked potentials may provide a more sensitive index of sleepiness than ongoing EEG measures. Broughton et al. (1982) and Broughton et al. (1981) also reported ERP changes when no changes were detected on a very sensitive vigilance performance task.

Findings of special interest for the present proposal were recently published by Peeke, et al. (1980). These investigators were interested in the combined effects of sleep deprivation and blood alcohol levels on performance measures and ERPs. Although they tested at only one, relatively short duration of deprivation (26 hrs) and were not interested in a recovery function, they found that sleep deprivation affected both performance and ERPs. The latency of components identified as N130 and P200 increased with sleep deprivation and P200-N330 amplitude increased. Thus, manipulation of sleep loss in normal subjects produced ERP changes in association with performance changes.

Gauthier and Gottesman (1983) also showed ERP changes in response to sleep loss. Of relevance to this study was the finding that 48-hrs of sleep deprivation increased the latencies of P1 and N1 and reduced the amplitudes of N1 and P2.

The studies reviewed suggest that ERPs may be useful measures for differentiating 1) different sleep stages, 2) waking from sleeping and 3) different levels of sleepiness during EEG indications of wakefulness. Studies are now needed involving systematic manipulations that go beyond demonstrations. Research is especially needed assessing different levels of sleepiness in the waking state.

1.2.3 Research Questions

The purpose of the present research is to examine examine the relationship among different components of ERPs, different amounts of sleep deprivation and recovery sleep, and performance. The data obtained may indictate that ERPs provide a sensitive index of changes in sleepiness. Such a finding would be significant in both basic and applied research settings concerned with the effects of altered sleep/wake schedules on performance. Finding an evoked response-performance relationship may, however, have much broader implications. That is, such a relationship may be observed in a variety of situations in which performance is altered by unfavorable influences such as heat and cold stress, fatigue, chemical agents. It is possible that evoked potentials will be found to be closely related to more general constructs such as peformance readiness.

The present research addresses four main questions. The first question concerns the effects of sleep deprivation on event-related potentials. Previous research has shown that a relationship exists, the present study will attempt to replicate and extend these findings by periodically (every four hrs) collecting ERP recordings during a 48-hr test period during which some subjects are deprived of sleep while other subjects are tested but not deprived of sleep.

A second question concerns the relationship between time-of-day and ERP recordings. Time-of-day comparisons may permit the assessment of sleep-deprivation effects on the influence of circadian rhythms.

Our third question relates to the effects of different durations of recovery sleep on ERPs. To address this question, sleep deprived subjects will be divided into three groups and given one, two, and four hrs of recovery sleep. ERP recordings following recovery sleep will be compared to those obtained prior to sleep recovery.

The fourth question concerns the relationship between the changes in the characteristics of ERPs and changes in performance. Of particular interest is whether ERP changes associated with sleep loss can be used to predict performance changes associated with sleep loss.

2.0 METHODS

2.1 Subjects

The subjects were 40 male undergraduates who were screened for health problems and given a medical exam by a physician prior to the experiment. Twenty subjects were recruited and tested at the University of Southern Mississippi and 20 were recuited and tested at Bowling Green State University. Informed consent was obtained in writing after all details of the research project were fully described. The importance of full participation was noted, but subjects were also told that they were free to terminate their participation at any time. The subjects were told that they would be paid for each day of their participation and would receive a 30 dollar bonus for full participation. All subjects completed the experiment and were paid 120 dollars.

2.2 ERP Measures

2.2.1 Stimuli and Tasks

An "odd ball" task was used to elicit ERPs. Auditory stimuli were presented in Bernoulli series of low pitched, non-target tones (1000 Hz) and high pitched (1500 Hz) target tones (.5 sec, 65 dB), which were delivered binaurally through earphones. The subjects were instructed to "tap your foot" upon hearing a target tone and to count the total number of such tones. Non-target tones were presented 80% of the time and target tones 20 %. The intertone interval was 1.5 sec.

The odd ball task was either presented alone or concurrently with an "easy" or a "hard" version of a tracking task. The tracking task was implemented on a microprocessor and involved the subject manipulating a control stick to keep a cursor either on a moving target ("chase") or away from a moving target("run"). The chase and run modes alternated unpredictably and the speed of the target was varied to make the task "easy" or "hard".

2.2.2 ERP Recordings

ERPs were recorded to the high pitched target tones. The recording epoch extended from the onset of the tone for a period of 800 ms. A trial consisted of 35 target tones, i.e. ERPs were averaged over 35 target tones. To maintain attention the number of target tones varied on any given trial although the number of target tones averaged remained constant at 35.

ERPs were recorded for four consecutive trials during each test block. During the first two trials, the oddball task alone was presented (ERP only). During the last two trials the "oddball" task was superimposed over the easy and hard versions (in random order) of the tracking task (ERP/Tracking).

The ERPs were recorded from Cz - A1 with impedance values less than 10,000 Ohms. Signal averaging was performed by an Apple II plus microprocessor equipped with an RC Electronic Computerscope signal averager. The ERP signals were amplified by a Grass Model 7P122 low-level DC amplifier (TC .8, sensitivity at .05, high pass filter at 35). The artifact rejection mode was in place whenever possible to avoid movement or other sources of contamination during a tone presentation (the artifact threshold level was set at the lowest posible value for each subject).

2.2.3 ERP Analysis

Visual analysis was used to identify components (P1, N1, P2, N2, P3) of the evoked responses. The latency of each component was then obtained by finding the time from stimulus onset to the peak of the waveform. Peak-to-peak amplitudes were calculated by finding the voltage difference between P1N1, N1P2, P2N2, and N2-P3. Absolute amplitude was found for P1, N1, P2, N2, and P3.

2.3 Behavioral Measures

2.3.1 Performance Assessment Battery (PAB)

The Performance Assessment Battery (PAB), developed at the Walter Reed Army Institute of Research, is a computer controlled multi-task array which was designed to measure subtle changes in cognitive processing. Test items are presented via video monitor, and subject responses are recorded through input on an alphamumeric key-board. The PAB has been used as a measure of performance decline in previous studies (e.g., Thorne et al., 1983) and has been shown to be an effective measure of performance deficits during 72-hrs of sleep deprivation. The following seven tasks comprise the assessment battery used during the present study. Completion of the battery required about 25 min.

<u>MAST 6</u> - a visual search and recognition task. Six target letters are presented at the top of the screen. The subject is required to determine whether the target letters are present in a series of 20 letters presented in the middle of the screen. The "S"ame key is pressed if the target letters are present, and the "D"ifferent key is pressed if none or only some of the target letters are present.

<u>LOGICAL</u> - a task of syllogistic reasoning. The subject is presented with a statement about the relationship between two letters. Following the statement, a two letter combination is presented. The subject is required to determine whether the statement correctly or incorrectly describes the order of the two letters. Again, the "S"ame and "D"ifferent keys are used to signal agreement or disagreement, respectively.

<u>PROBE-MEM</u> - a task of short-term memory recall. A series of nine random numbers are presented simultaneously in the middle of the screen for a short interval. The screen then blanks, and eight of the nine numbers reappear in a

different random order. The subject is required to detect the missing number and signals this number by entering it through the numeric key pad.

SERIAL ADD/SUB - a task of mental addition and subtraction. Two single-digit random numbers and either a plus or minus sign are presented in sequential order in the middle of the screen. The subject is required to perform the given operation, using the two numbers in their order of presentation. The single digit answer is then entered through the numeric key pad. An actual answer greater than +9 must first be transformed by subtracting 10, and then entering the result. If the actual answer is negative, the 10 must be added, and the result entered.

MATRIX 2 - A task of spatial memory. A random pattern of 14 asterisks is presented on the screen for a short interval. Following a short retention interval, another pattern of asterisks is presented on screen. The subject decides whether the two patterns are the same or different, and signals accordingly.

WILKINSON - a visual motor coordination task. The subject is presented with a small box with four red lights displayed in a square pattern on the top on the box, and four black buttons displayed in the same pattern below the lights. The lights are then turned on one at a time in a random order, and the subject is required to quickly press the button which corresponds to the illuminated light. The task lasts for eight minutes.

MOOD SCALE - a scale designed to assess current mood state. The subject is presented with 65 adjectives which describe a mood, and is asked to rate each adjective on a scale of 1 to 5 as they reflect current feelings.

Although reaction time and accuracy of performance are traditional measures utilized in sleep deprivation research, theoretically, either one of these measures alone may be insufficient to describe performance decrements during sleep deprivation. For example, the subject may choose to work at a slower rate in order to increase accuracy, or to increase speed by sacrificing accuracy. Because of this trade-off function between speed and accuracy, in the present study, these two measures were combined into a third measure called "throughput". Throughput is a measure which gives the rate of successes per given unit of time. throughput is derived numerically by calculating percent correct and dividing by the mean reaction time, and multiplying by a constant.

2.3.2 Two-Hand Reaction Time Task

This was a microprocessor-based reaction time task. Subjects were seated before a monitor. They were instructed to place two fingers of their left hand on the "3" and "4" key and two fingers of their right hand on the "7" and "8" key. At the beginning of a trial, four squares appeared on the monitor. One by one, three of the squares disappeared leaving one square. The subject's task was to press the key corresponding to the position of the remaining key. That is, if the last remaining light during the trial was the extreme right key, the subject was to press the "8" key. If the remaining light was the second from the right, he was to press the "7" key. If the remaining light was second from left, he was to press the "4" key. And if the remaining light was on the extreme left, the "3" key was to be pressed. Four sets of 25 trials were presented with a 30 s rest period between each set.

2.3.3 Short-Term Memory Task

This task was a microprocessor-based memory task. Subjects were seated before a monitor on which was presented a set of 7 letters. After presentation of the seven letter set was completed, one randomly selected letter from the same set was presented. The subjects task was to identify the serial position of that letter by depressing the corresponding number key on the keyboard.

2.3.4 Continuous Performance Task : Visual and Bimodal

This was a microprocessor-based signal detection task. For the visual CPT subjects were seated before a monitor on which a series of many letters were presented. The subject was required to respond (depressing any keyboard key)) whenever the letter "A" was followed by the letter "H". The same procedure was followed for the bimodal task except that some letters were presented in the visual mode and others presented in the auditory mode via a speech synthesizer. The visual and auditory mode stimuli were varied randomly.

3.0 Procedure

Forty subjects served in the experiment. Thirty in the experimental condition (48-hrs sleep deprived)and 10 in the control condition (non-sleep deprived). Twenty subjects were tested in the University of Southern Mississippi laboratory and twenty subjects were tested in the Bowling Green State University laboratory. The subjects at both centers were tested in groups of four on the same days of the week (Wednesday through Sunday) during five consecutive weeks.

Subjects were be asked to report to the sleep laboratory at 2200 hours on the first day of the experiment and were given final release from the laboratory at no later than 1330 hours on the last day of the experiment. On the first two nights, the subjects slept in the laboratory to ensure initial levels of sleep and also for adaptation to laboratory conditions. They received practice sessions with the behavioral tasks from 2200 to 2300 hours on both nights. They were not required to remain in the laboratory during the daytime hours of the first two days.

The subjects were awakened at 0700 on Day 3 following their second sleep night in the laboratory and the experimental subjects were kept awake until Day 5. The control subjects were permitted to sleep during each of the test nights from 2400 to 0700 with the exception of an awakening at 0400 for the recording of ERPs. Data collection for the experimental subjects began at 0800 hours on Day 3 with measures obtained from each task every 4 hrs until the conclusion of the experiment. The control group was tested following the same schedule except during their sleep periods.

The subjects spent approximately three hrs of each four- hr test block in testing. During their free time they were permitted to read, study, play video games, etc. but were not allowed to leave the area or to sleep. Meals were provided and snacks and beverages were freely available during free periods. Caffeinated beverages and smoking were permitted but at only levels that the subjects described as normal before they began the experiment. Aspirin or acetominophen were the only medications permitted.

The subjects were tested at microprocessor work stations. The order of task presentation was varied across subjects but did not vary across test blocks. All task orders were equally represented in each group of subjects.

3.1 <u>Naps</u>

On the last day of sleep deprivation, the experimental subjects were randomly divided into three groups for assessing the effects of three different durations of recovery sleep (1, 2, or 4 hrs). Each subject then received two additional ERP trials immediately upon awakening from recovery sleep. One hour after awakening, the subjects were administered the Performance Assessment Battery. The control group was tested in similar fashion after waking from their night's sleep. At the conclusion of the experiment, subjects were allowed the option of sleeping until rested in the sleep laboratory or of being driven to their homes.

3.0 Results

3.1 ERP Measures-Amplitude

ERPs were scored following visual inspection of the overall waveform to identify the location of the components referred to as P1, N1, P2, N2, and P3. The latencies and amplitudes of the components for the first two trials (no concurrent task; ERP only) of the ERP test session were then averaged together. Similarly, the latencies and amplitudes of the components from trials three and four (subjects were performing a tracking task while ERPs were being recorded; ERP/Tracking) were averaged together. Separate analyses were not conducted for the easy and hard versions of the tracking tasking because of missing data. The evoked potential data from three of the subjects was found to be unscorable.

ERP records were scored to obtain both absolute amplitudes and peak-to-peak amplitudes. Separate analyses were conducted for ERP only and ERP/Tracking trials. With regard to absolute amplitudes, it was found that P1, N2, P2, and P3 all tended to change in amplitude from the first to the last of the 12 four-hr test blocks. P3 showed by far the clearest and most orderly change and is described below. Data for the remaining components are presented in Appendix 1. Analysis of the peak-to-peak amplitude changes were conducted primarily to substantiate the changes observed in the absolute amplitudes. The desirable feature of the peak-to-peak measure is that it is obtained independently of baseline voltage which may vary from subject to subject and across time within subjects. It was found that N1P2 tended to increase while N2P3 tended to decrease across test blocks. N2P3 changes were greater and are described below. N1P2 changes are described in Appendix 1.

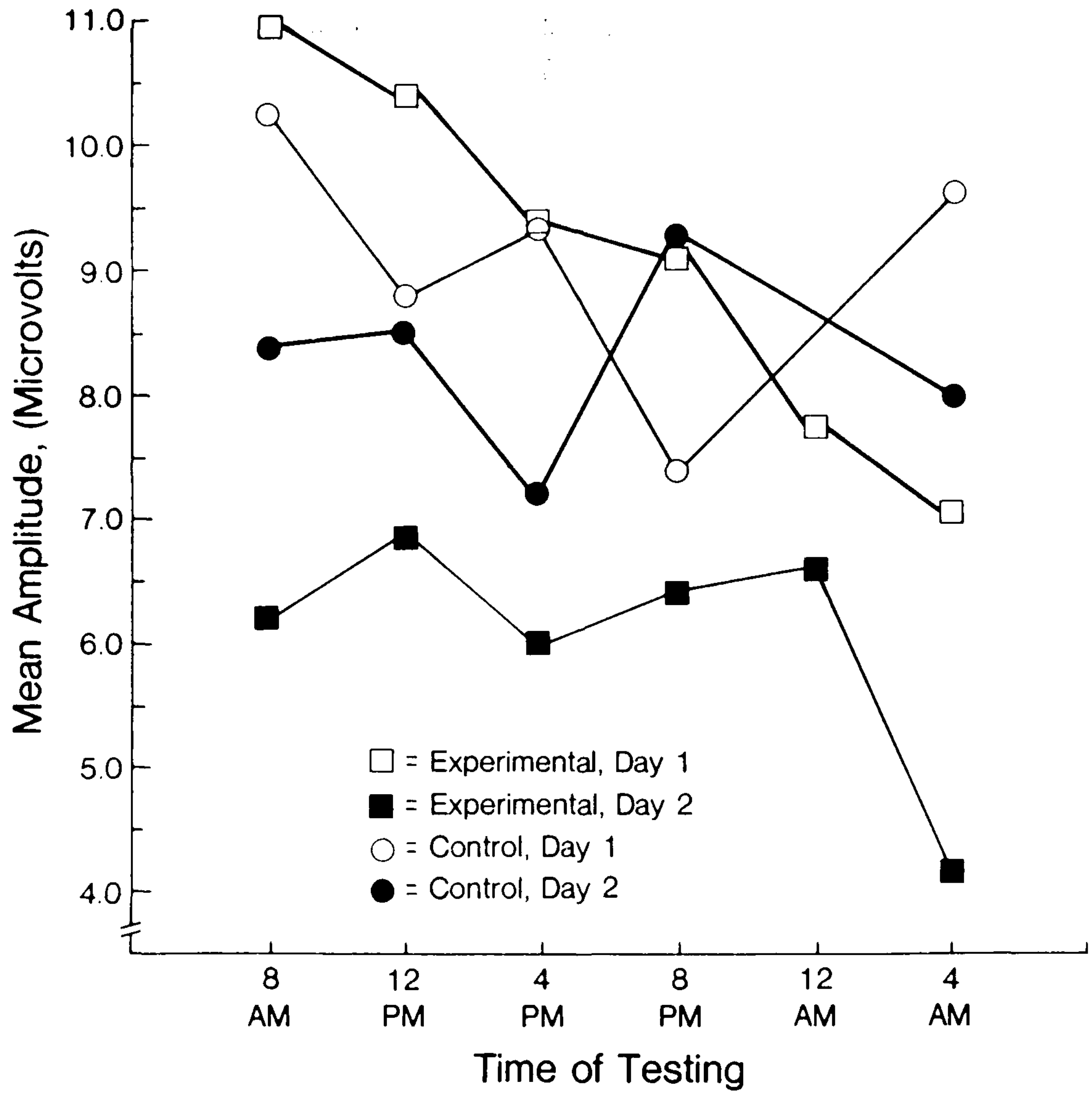
3.1.1 P3 Amplitude

Figure 1 illustrates the mean P3 amplitude (in microvolts) as a function of Day (Days 1, 2) and time of day (Blocks 1-6) for experimental and control subjects. The data were obtained from the ERP only trials. Similar data were obtained from the ERP/Tracking trials (See Appendix 1).

As can be seen, the P3 component markedly decreased in amplitude across the two days of deprivation. This diminution effect is evident within each day of deprivation but the reduction in amplitude was more systematic across the testing blocks of Day 1. The latter suggests a testing effect at least partially accounts for the diminution. For the experimental subjects only, a 2 X 6 analysis of variance was performed for Days (1,2) X Blocks (1-6). The statistical analysis confirmed a main effect for Day in that significantly smaller P3 amplitudes occurred on Day 2 than on Day 1, $F(1,27) = 39.43$, $p = .001$. There was also a significant Block effect, $F(5,135) = 7.24$, $p < .001$ and a significant Day X Block interaction, $F(5,135) = 2.54$, $p < .05$ (The Geisser Greenhouse conservative F test was used here and in other analyses where

Figure 1. P300 amplitude (in microvolts) for the Experimental and Control groups for each time of day on both test days.

Auditory Evoked Response - P300 Amplitude



there was evidence of asymmetry of the covariance matrix). The Day X Block interaction is consistent with the observation that a a decrement across Blocks occurred on Day 1 but not Day 2. The repetition of low amplitudes found on Blocks 1 and 6 on both Days of the experiment suggests a circadian rhythm.

A second analysis was performed which included Group (experimental vs control) as a factor . This analysis was a 2 X 2 X 5 mixed analysis of variance which includes Groups (experimental, control) X Day(1,2) X Block(1-4, 6) effects. Only Blocks 1 - 4 and 6 were assessed since the control subject data were available only for these Blocks. A significant main effect for Day was again found, $F(1/35) = 16.82$, $p < .01$, as well as a Day X Group interaction, $F(1/35) = 6.87$, $p < .05$. The latter is due to P3 amplitude being smaller on Day 2 than Day 1 for experimentals but not for controls. The latter suggests that P3 was affected by sleep deprivation.

3.1.2 N2-P3 Amplitude

As was seen with P3 amplitude, N2P3 amplitude for the experimental group decreased markedly from the first to the second day. Once again the decrease across test blocks was greater on the first day than on the second. The values for the control group also diminished across test blocks indicating a possible te^ting effect. A Days (2) X Blocks (6) analysis of variance of N2P3 amplitude revealed a significant Day effect, $F(1,27) = 40.39$, $p < .001$ confirming the observation of significantly smaller amplitudes on the second day. A significant Block, $F(5,135) = 8.99$, $p < .001$, and significant Day by Block interaction, $F(5,135) = 4.65$, $p < .01$, also confirmed that the changes across blocks differed on Day 1 and Day 2. Although the decrease in amplitude from Day 1 to Day 2 can be seen to be greater (Figure 2), a Groups (2) X Days (2) X Blocks (6) analysis of variance failed to yield evidence that the control group means differed from the experimental group means on either day. This may have been due, however, to an unusually large amount of variance in the control group means.

3.2 ERP Measures-Latency

ERP latencies were also affected by the test conditions. The effects were more pronounced on the ERP/Tracking trials than on the ERP-only trials, and only the former will be described. Also, statistically reliable changes (increases) associated with sleep deprivation were seen only for the P2, N2, and P3 components. Effe ts for N2 and P3 are larger and are described below.

3.2.1 P3 Latency

Figure 3 illustrates the mean P3 latencies (in ms) for the ERP/Tracking trials for both days of the experiment and time of day. It can be seen that P3 latency remained between 320 and 300 ms through all of the first test day and most of the second for

Figure 2. N2P3 amplitude (in microvolts) for the Experimental and Control groups for each time of day on both test days.

Auditory Evoked Potentials - N2P3 Amplitude

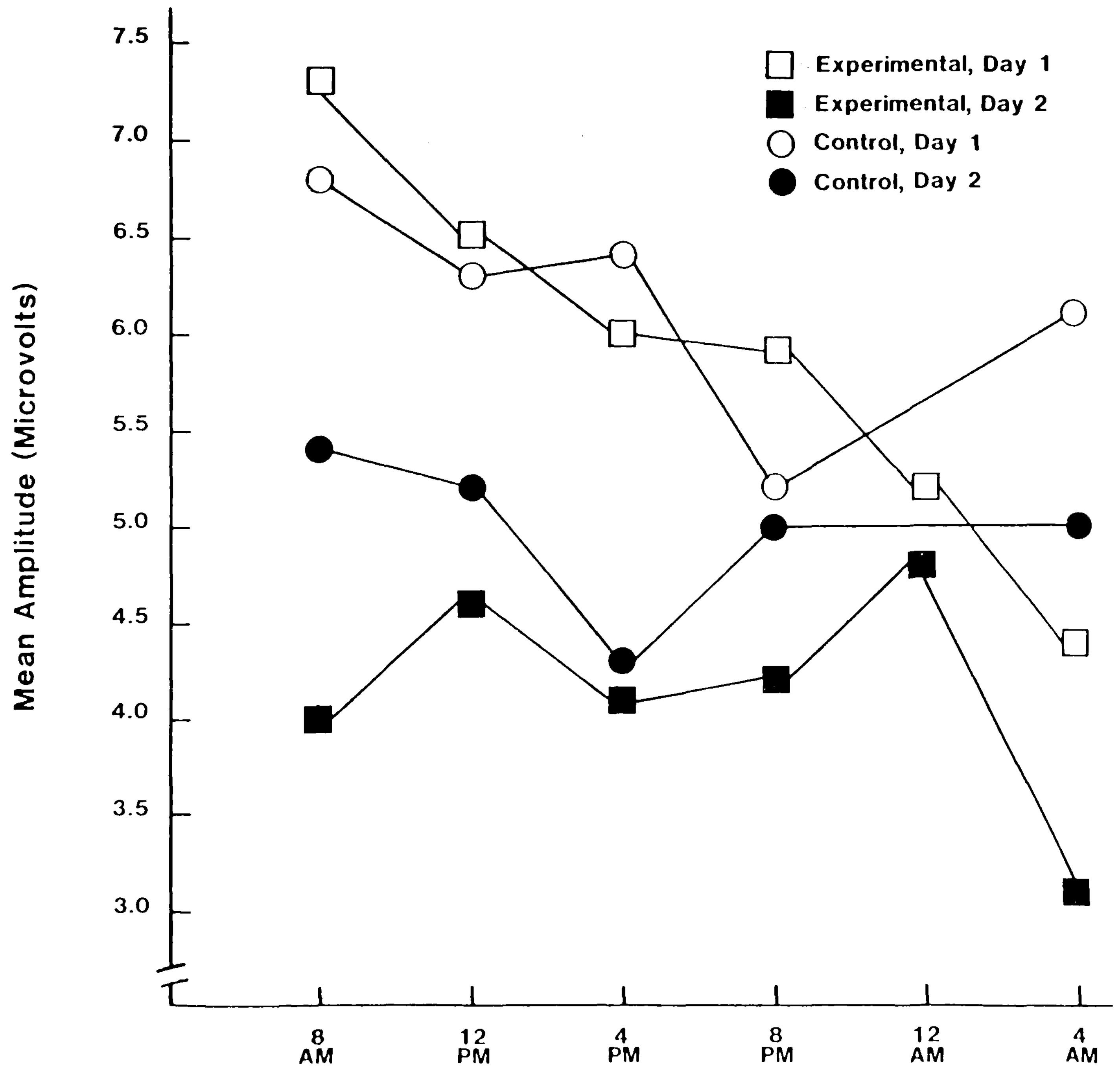
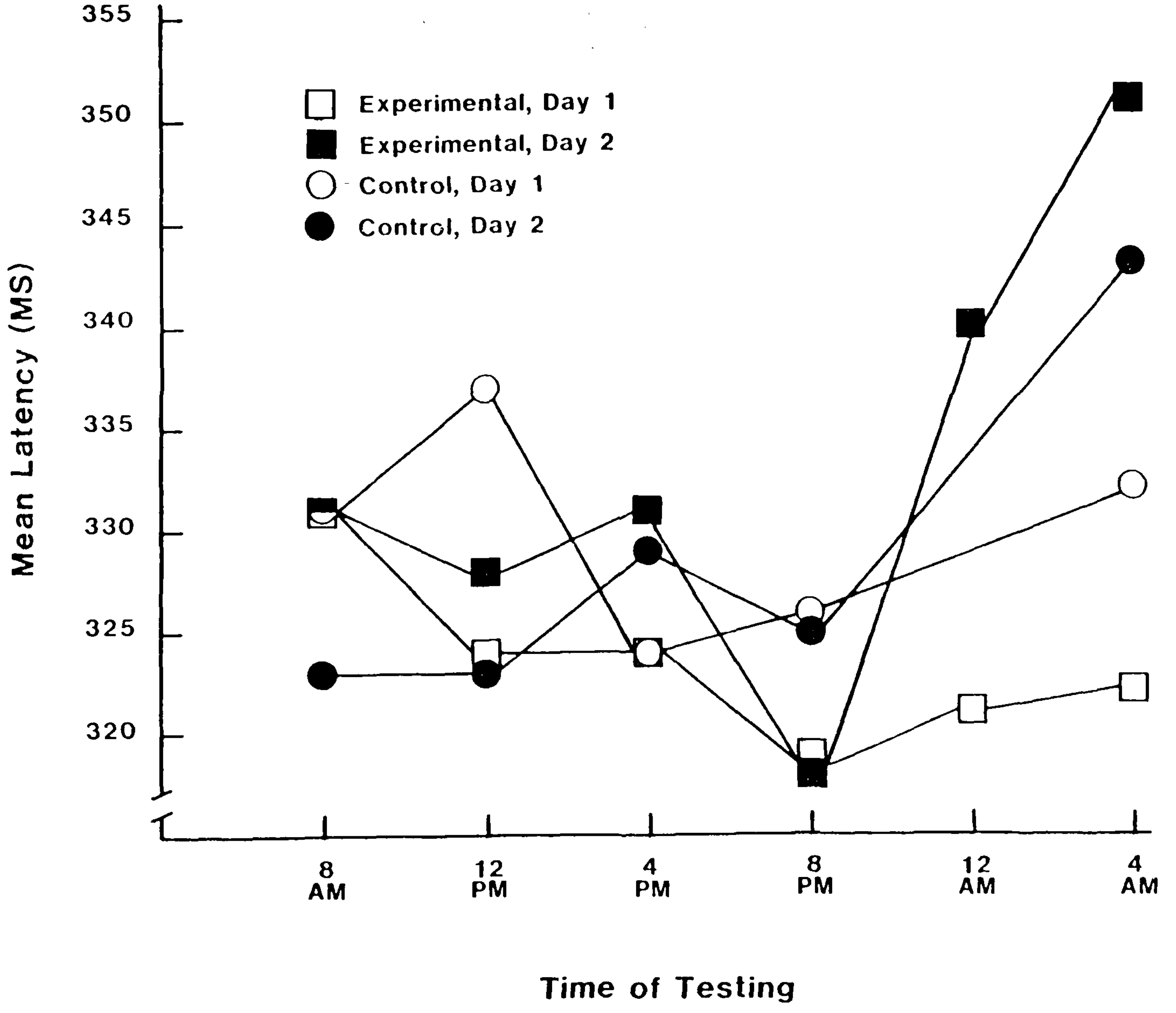


Figure 3. P3 latency (in ms) for the Experimental and Control groups for each time of day on both test days.

Auditory Evoked Response – P300 Latency



both the experimental and the control group. There was a 30 ms increase in latencies, however, during the last two test blocks of the 48-hr session for the experimental group. A smaller increase was also seen for the control group on the very last test block. A Days X Blocks analysis of variance of P3 latencies revealed significant Day effect, $F(1,27) = 13.06$, $p < .01$; Block effect, $F(5,135) = 4.43$, $p < .01$; and a Day by Block interaction, $F(5,135) = 2.83$, $p < .05$. This statistical outcome can be attributed to longer P3 latencies on Day 2 than on Day 1, primarily because of the longer latencies on the last two test blocks. A Group X Day X Block analysis of variance yielded a marginally significant Group X Day interaction, $F(1/35) = 3.18$, $p = .08$, reflecting the tendency for the latency for the two groups to be different on Day 2 but not Day 1.

3.2.2 N2 Latency

Figure 4 presents N2 latency for each test block (time of day) for both days of the experiment. A sleep deprivation effect is more apparent with N2 latency. That is, it can be seen that N2 latencies for the experimental group were relatively stable during the first four test blocks (223 ms on three of the four blocks) of the first day, and then increased approximately 20 ms over the last two test blocks. The same pattern is evident for Day 2 except there is a 30 ms increase during the last two test blocks. This pattern suggests both a sleep deprivation effect and a time-of-day (circadian) effect. This pattern was not seen in the control group. The latencies for the control group were stable (usually between 240 and 250 ms) until the very last test block. Although there is only a small difference in the Experimental and Control group values during the last test block, note that the Control group means were 20-25 ms longer on the first day. A Days (2) X Blocks (6) analysis of variance of N2 latencies revealed a significant Day effect $F(1,27) = 74.75$, $p < .001$, confirming the longer latencies on Day 2; and a significant Block effect, $F(5,135) = 11.18$, $p < .001$, confirming the time-of-day effect. A Groups (2) X Days (2) X Blocks (5) analysis of variance was used to explore possible effects of repeated testing. A significant Day X Group interaction, $F(1,35) = 9.48$, $p < .01$, supported the observation of a deprivation-related increase in latencies for the Experimental but not the control group.

3.3 ERP Measures - Effects of Recovery Sleep

To assess the effects of recovery sleep on the evoked potentials, the change from the very last of the 12 test blocks (Block 6, Day 2) to the ERP following recovery sleep was submitted to analysis. Table 1 contains the amplitude changes as a function of nap duration, for the P1, N1, and P2 components. A one-way analysis of variance of the change scores is also presented as are the results of a mean comparisons using the Duncan Multiple Range test. Analysis of the remaining ERP measures failed to yield significant differences.

Figure 4. N2 latency (in ms) for the Experimental and Control groups for each time of day on both test days.

Auditory Evoked Response – N200 Latency

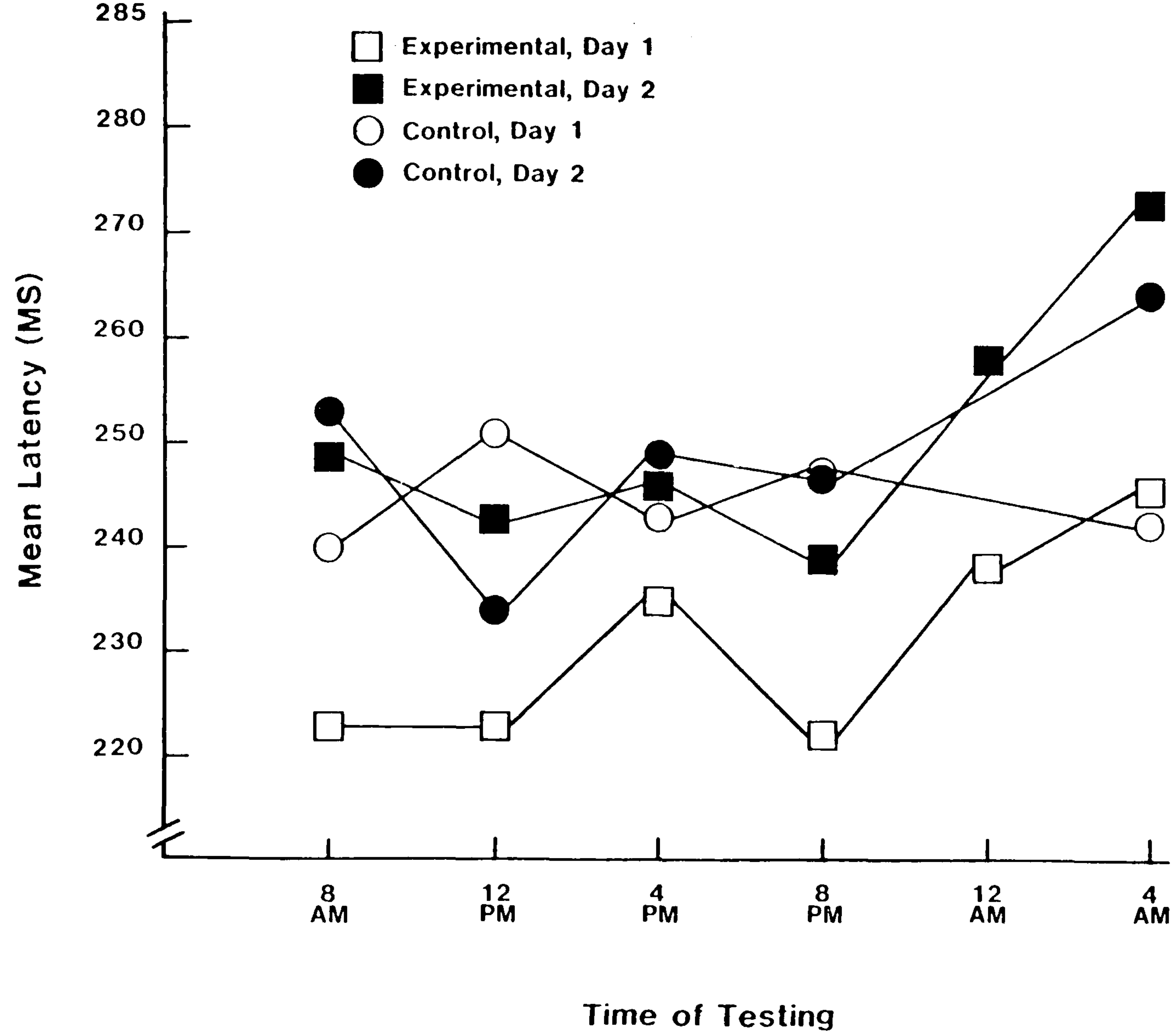


TABLE 1

Change (in microvolts) of P1, N1, and P2 from the last test Block to post-recovery sleep

P1 Amplitude

	1-HR	2-HR	4-HR	CONTROL
Mean	-2.08	-0.42	-0.21	.72
s.d.	2.40	2.78	1.01	1.89

GROUPS - $F(3,31) = 2.77$, $p < .06$
1-hr < 2-hr = 4-hr = control

N1 Amplitude

	1-HR	2-HR	4-HR	CONTROL
Mean	-2.05	-0.87	-0.32	0.39
s.d.	1.71	1.23	1.25	1.02

GROUPS - $F(3,31) = 5.38$, $p < .01$
1-hr < 2-hr = 4-hr = control

P2 Amplitude

	1-HR	2-HR	4-HR	CONTROL
Mean	-1.15	-0.88	-0.77	0.74
s.d.	1.64	0.89	1.23	0.71

GROUPS - $F(3,31) = 4.63$, $p < .01$
1-hr < 4-hr

It is evident for each component, that all nap durations (1, 2, 4 hrs) resulted in a very sharp decrement in amplitude. For example, P1 amplitude decreased in amplitude by more than two microvolts. The decrement was most severe for the 1-hr nap and more moderate for 2-hr and 4-hr naps. The control subjects in each case showed slight increases in amplitudes.

3.4 Behavioral Measures

3.4.1 Performance Assessment Battery (PAB)

In the analysis of the throughput measure for the six performance tests of the PAB, a predeprivation baseline was established for each subject by finding the mean of the first four test blocks. Statistical analysis was then performed on the percentage change from baseline of the scores from each test block. Percentage change values for each of the tasks for each of the 12 test blocks for the experimental group only are shown in Figure 5.

Consistent with the expected deprivation effect there was, on the average, a marked deterioration of performance for five of the six tasks especially towards the end of the second day of deprivation. For the same five tasks, performance was poorest during the last block of sleep deprivation (hours 44-48) with performance decrements ranging from 15% to 35% below baseline.

It is also apparent from Figure 5, that circadian factors affected responding on the five tasks. The lowest level of performance on both days tended to occur during the late night (0800-1200) and early morning (0400-0800) hours. There was also a tendency for the peak performance to occur during the evening hours (2000-2400) on the first day and the early afternoon hours (1200-1600) on the second day.

An exception to the above was performance on the MAST6 task. Although there appeared to be a time of day effect consistent with that seen for the other tasks, performance on Day 2 was higher rather than lower than on Day 1. The sharp and unexpected increase in performance on Day 2 was found for both the experimental and control groups.

A 2 (Days 1 & 2) by 6 (6 4-hr test blocks) analysis of variance was performed on the throughput measure for each of the tasks for the experimental group only. The results of these analyses are shown in Table 2.

Inspection of Table 2 reveals that the analysis of variance supported the observations made above with significant Day effects due to lower performance on the second day and significant Block effects indicating performance changes across time of day. Post hoc tests revealed that the significant Day by Block interactions for the Probe-Mem and Wilkinson tasks can be attributed to an increase in performance from the 2000-2400 to the 0400-0800 test block on one of the days and a decrease on the other. For the Probe-Mem task, the interaction effect was due to

Figure 5. Mean throughput (percentage change from baseline) for each of the tasks of the Performance Assessment Battery across the 12 4-hr test blocks. Experimental group only.

PERFORMANCE ASSESSMENT BATTERY

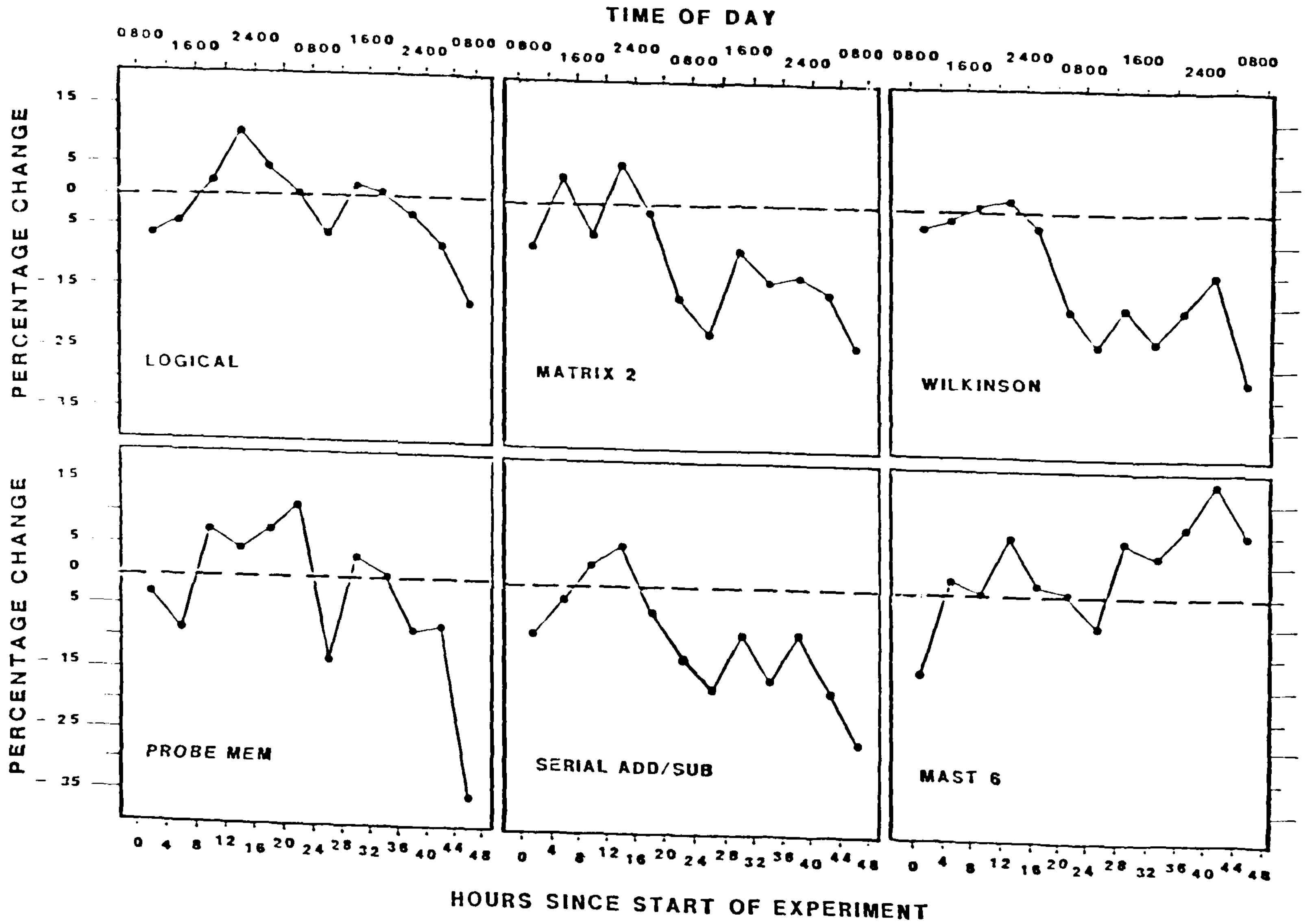


Table 2. Results of a 2 (Days 1 & 2) by 6 (6 4-hr test blocks) analysis of variance of the throughput measures for each PAB task (Experimental group only).

DAY EFFECTS

TASK	df	F	prob.
Logical	1/29	3.51	.0714
Probe-Mem	1/29	15.47	.0005
Matrix 2	1/29	6.20	.0190
Add/Sub	1/29	14.72	.0007
Wilkinson	1/29	58.31	.0000
Mast6	1/29	2.19	.1499

BLOCK EFFECTS

TASK	df	F	prob.
Logical	5/145	2.62	.0411
Probe-Mem	5/145	1.69	.1566
Matrix 2	5/145	3.69	.0077
Add/Sub	5/145	5.17	.0008
Wilkinson	5/145	13.15	.0000
Mast6	5/145	3.94	.0070

DAY BY BLOCK INTERACTIONS

TASKS	df	F	prob.
Logical	5/145	2.99	.0236
Probe-Mem	5/145	4.06	.0041
Matrix 2	5/145	.31	.8690
Add/Sub	5/145	.95	.5085
Wilkinson	5/145	2.73	.0426
Mast6	5/145	.62	.6342

performance increasing during the three test blocks from 1200 to 2400 on the first day and decreasing during these same test blocks on the second day.

A Groups (Experimental, Control) X Days (1,2) X Blocks (4) analysis of variance of throughput was used to compare the performance on the PAB of the experimental subjects with the control subjects. Only Blocks 1-4 were used in the analysis because the control group subjects slept during Blocks five and six. Of interest in this analysis was whether a single night of sleep deprivation would result in the experimental group showing lower daytime performance relative to a control group which was repeatedly tested but allowed to sleep. A Groups X Days interaction was found for the Logical task, $F(1/38) = 14.07$, $p < .001$, the Wilkinson task, $F(1/38) = 20.23$, $p < .0001$, and the Serial Add/Sub task, $F(1/38) = 3.56$, $p = .07$. Follow-up analyses showed that, for these three tasks, the performance of the experimental groups differed on the second day but not the first. No significant effects were found on the remaining tasks.

3.4.1.1 Effects of Recovery Sleep

Table 3 presents the means and standard deviations of the throughput values (percentage change from baseline) obtained following the recovery sleep given to the Experimental subjects following 48 hrs of testing.

The relationship between nap conditions was investigated using a one way analysis of variance of the post-recovery sleep throughput values (percentage change from baseline). A significant effect of conditions was found for the Wilkinson task, $F(3/36) = 6.67$, $p < .05$, the Logical task, $F(3/36) = 5.60$, $p < .01$, and the Serial Add/Sub task, $F(3/36) = 4.28$, $p < .05$ Post hoc tests revealed that Four-hr group post-nap means were at control group levels for the Wilkinson task only. The Four-hr group post-nap means, however, were higher than the One-hr and Two-hr group post nap means on the Logical task as well as the Wilkinson task. The Control group mean was higher than all other group means on the Serial Add/Sub task. Comparison of the post-recovery sleep means with the pre-recovery sleep means indicated that the former for some tasks were considerably higher. This may have been due to an incentive effect as the subjects were aware that completion of the final PAB task marked the end of the experiment.

3.3.2 Short-Term Memory Task (STM)

Two dependent variables were computed for the STM task: total number correct and the total number of timed-out errors. For each subject, the total number correct (TCOR) was the sum of the number of trials in which a subject responded with the correct serial position of the target letter. The total number of timed-out errors (TOUT) was the sum of the number of trials in which a subject did not make a response within the response time allotted.

Table 3. Means and standard deviations for the final administration of the PAB. Experimental subjects had received 1, 2, or 4 hrs of recovery sleep.

	Control	Four Hour	Two Hour	One Hour
Logical	16.7 (27.0)	38.0 (30.4)	-.3 (20.1)	-4.1 (24.0)
Probe-Mem	6.1 (38.6)	24.8 (31.1)	15.7 (39.1)	-10.5 (30.3)
Matrix 2	8.5 (36.4)	-10.1 (30.2)	-2.3 (42.6)	-12.0 (35.8)
Add/sub	41.1 (32.6)	14.0 (32.8)	.9 (21.0)	.4 (28.5)
Wilkinson	11.4 (5.5)	8.1 (5.7)	-7.9 (16.6)	-12.2 (21.8)
Mast6	33.5 (31.5)	-7.7 (29.0)	22.4 (46.0)	25.6 (52.7)

Figures 6 and 7 illustrate mean TCOR and TOUT as a function of time of testing for experimental subjects only. It can be seen that there were fewer correct responses on Day 2 of sleep deprivation than on Day 1, means of 23.16 and 20.32 respectively, and that a greater number of timed-out errors occurred on Day 2, means of 2.38 and 3.63 respectively. Also, it is evident that in terms of TCOR that experimental subjects performed worse at block 6 (4 am) on Day 1 and blocks 5 (12 am) and 6 (4 am) on Day 2. With respect to TOUT, experimental subjects performed worse at blocks 5 and 6 on Days 1 and 2.

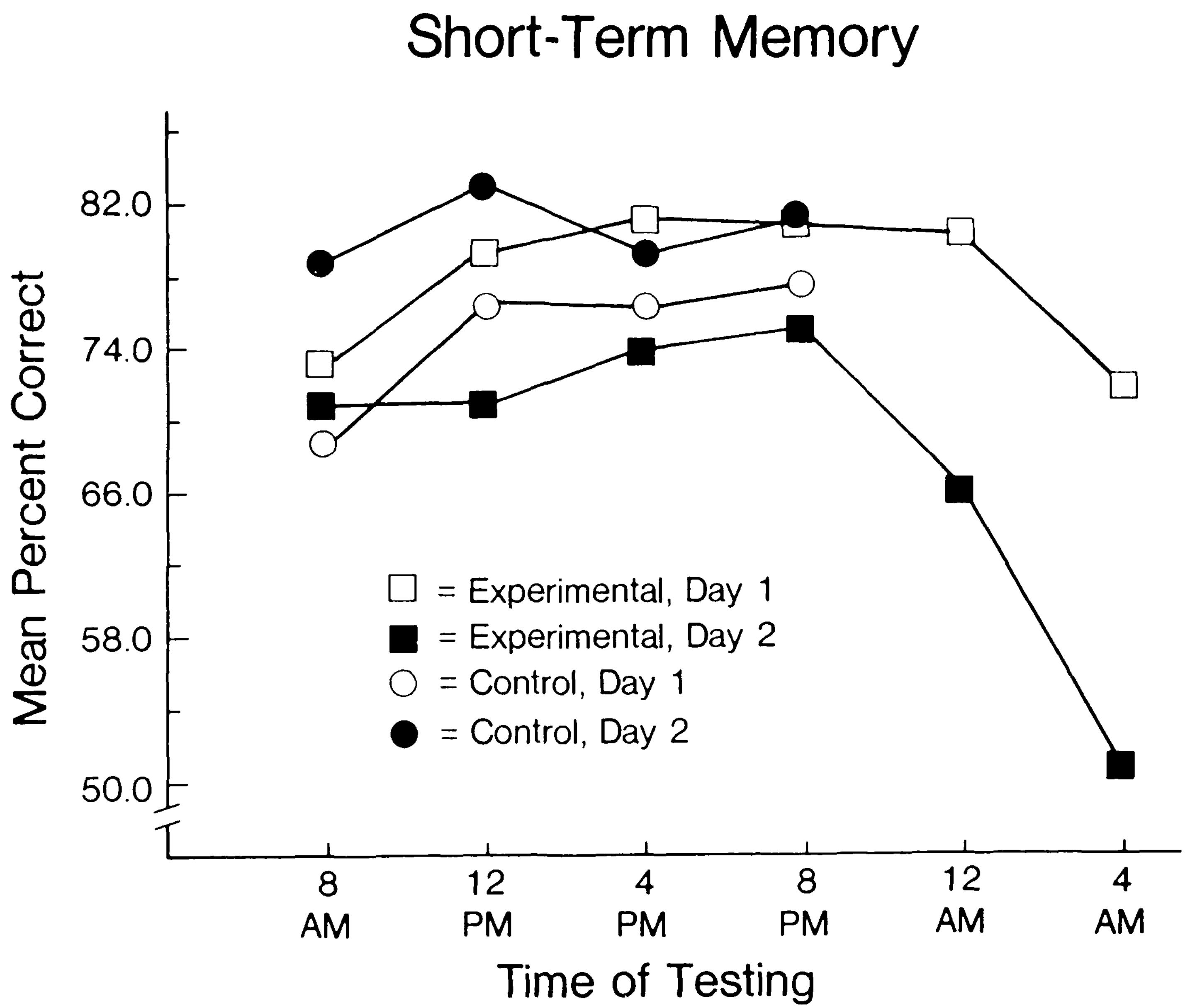
To assess the reliability of the observations of the Experimental group's performance, a 2 X 6 analysis of variance was performed on each dependent measure for Day (1,2) x Block (1-6) effects. A significant main effect for Day was found for TCOR $F(1/29) = 29.44$, $p < .0001$, and for TOUT $F(1/29) = 8.18$, $p < .01$. This confirms the above observations that there were significantly fewer correct and more incorrect responses on Day 2. This analysis also revealed a significant main effect for Block for TCOR $F(5/145) = 7.12$, $p < .0001$, and for TOUT $F(5,140) = 3.05$, $p < .05$. A Newman Keuls test for multiple comparisons was done to determine which blocks differed significantly. For TCOR Block 6 (4 am) was significantly different from all other blocks; there were fewer correct and more incorrect responses at 4 am than at any other time. For TOUT, Block 6 was significantly different from Blocks 2 (12 pm), 3 (4 pm), and 4 (8 pm) while Block 6 was not significantly different from Blocks 1 (8 am) and 5 (12 am), indicating that the greatest number of timed-out errors occurred at 4 am with the next greatest number of timed-out errors occurring at 8 am and 12 am. No Day x Block interactions were found.

A second analysis was done which included the Group factor (experimental vs control). A 2 X 2 X 4 analysis of variance was performed on each dependent variable for Group (experimental, control) X Day (1,2) X Block (1-4) effects. A significant main effect for Day was again found for TCOR $F(1,38) = 8.08$, $p < .01$, as well as a significant main effect for Block, $F(3,114) = 4.74$, $p < .01$. In addition to these main effects, a significant Group X Day interaction was found for TCOR $F(1,38) < 11.90$, $p < .001$, This interaction is accounted for by the sharp decline in the performance of experimental but not control group subjects on Day 2. There were no significant main effects or interactions found for TOUT.

3.3.3 Continuous Performance Task (CPT) - Visual

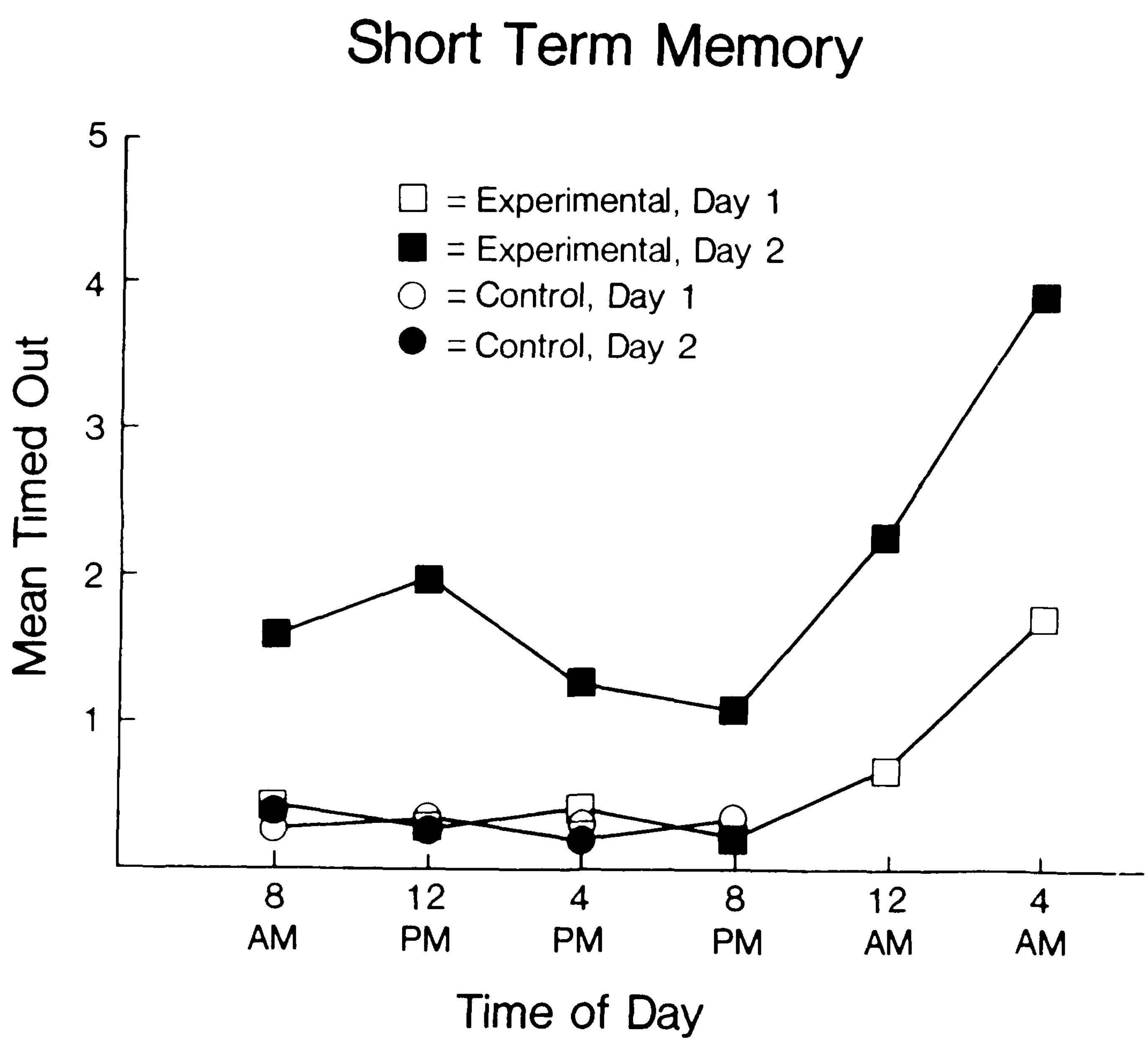
The CPT task yielded three dependent variables: mean number correct, mean errors of omission, and mean errors of commission. For each subject, the mean number correct was the average number of correctly identified A-H combinations, the mean errors of omission was the average number of A-H combinations not responded to, and the mean errors of commission was the mean number of responses in the absence of an A-H combination. Since errors of omission were directly related to the number correct, the

Figure 6. Mean number of total correct on the Short-Term Memory Task for the Experimental and Control groups for each time of day on both days.



Short-Term Memory
Mean Percent Correct
82.0
74.0
66.0
58.0
50.0
= Experimental, Day 1
= Experimental, Day 2
= Control, Day 1
= Control, Day 2
8 AM
12 PM
4 PM
8 PM
12 AM
4 AM
Time of Testing

Figure 7. Mean number of "timed out" on the Short-Term Memory Task for the Experimental and Control groups for each time of day on both days.


Short Term Memory
= Experimental, Day 1
= Experimental, Day 2
= Control, Day 1
= Control, Day 2
Mean Timed Out
5
4
3
2
1
8 AM
12 PM
4 PM
8 PM
12 AM
4 AM
Time of Day

analysis for the latter only is presented.

Figures 8 and 9 illustrate the mean number correct and the mean errors of commission as a function of time of testing for experimental and control subjects. In terms of the experimental subjects only, it can be seen that there were fewer correct responses on Day 2 of sleep deprivation than on Day 1, means of 11.78 and 14.33 respectively, and that there were more errors of commission on Day 2 than on Day 1, means of 4.24 and 2.22 respectively. It is also evident that, in terms of mean number correct, experimental subjects performed worse at test blocks 5 (12 am) and 6 (4 am) on both days of deprivation.

The reliability of these observations for the experimental subjects was assessed with a 2 X 6 analysis of variance performed on each dependent measure for Days (1, 2) X Blocks (1-6). A significant main effect for Days was found for mean number correct, F (1/29) = 89.45, p < .0001, and for mean errors of commission, F (1/28) = 7.67, p < .006. This confirms the above observations that there were fewer correct responses and significantly more errors on Day 2. The analysis also revealed a main effect for Blocks for mean number correct, F (5/140) = 10.95, p < .0001, A Duncan's Multiple Range Test for multiple comparisons revealed that Block 5 (12 am) was significantly different from Blocks 2 (12 pm) and 4 (8 pm), such that there were fewer correct responses at 12 am than at 12 pm and 8 pm. The test also showed the same relation with Block 6 (4 am) significantly different from all other Blocks. The Day X Block interaction was not significant.

A second analysis compared experimental and control conditions. A 2 X 2 X 4 analysis of variance was performed on each dependent measure for Group (Experimental, Control) X Days (1, 2) X Blocks (1-4) effects. Only Blocks 1-4 were used in the analysis since subjects in the control condition slept during Blocks 5-6. A significant main effect for Day was again found for mean number correct, F (1/38) = 77.93, p < .0001, and for mean errors of commission, F (1/38) = 11.94, p < .001. There was also a main effect for Group for mean number correct. Experimental subjects had significantly lower mean number correct, F (1/38) = 4.41, p < .05, than control subjects. There was a significant Group X Day interaction for number correct, F (1/38) = 22.96, p < .0001, and a marginally significant interaction for errors of commission, F (1/38) = 2.87, p < .09. Thus there were fewer mean correct responses on Day 2 relative to Day 1 for experimental subjects but not control subjects. A trend appeared for more errors of commission on Day 2 for the experimental subjects, but a Block X Day interaction only approached significance, F (3/114) = 2.36, p < .07.

3.4.4 Bimodal Continuous Performance Task (BIM)

The BIM task is simply a modified version of the CPT visual task, and as expected, results were similar. As seen in Figure 10, for mean number correct, the BIM task proved even more sensitive than

Figure 8. Mean number of correct on the Continuous Performance Task - Visual for the Experimental and Control groups for each time of day on both days.

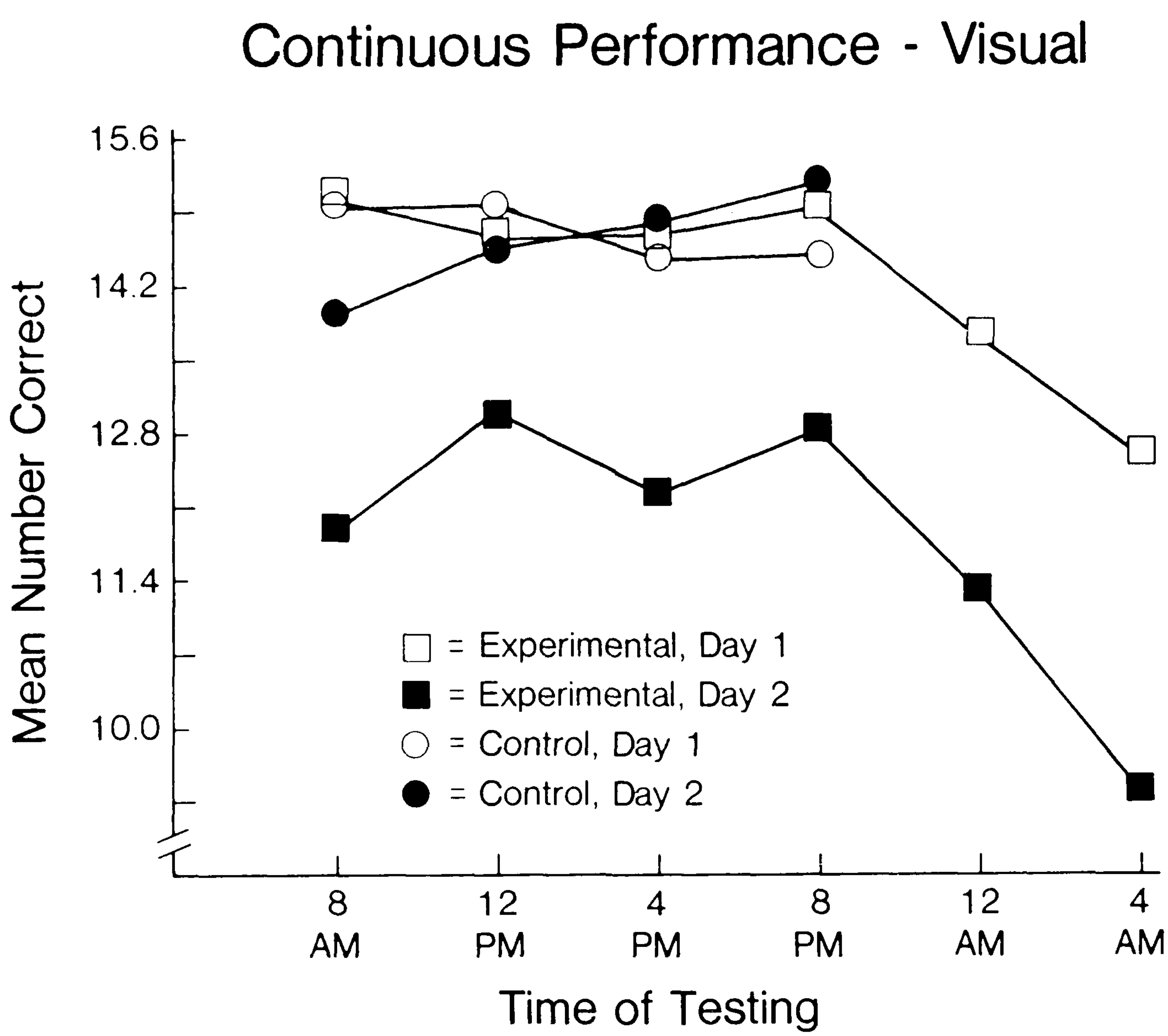

Continuous Performance - Visual
Mean Number Correct
15.6
14.2
12.8
11.4
10.0
8 AM
12 PM
4 PM
8 PM
12 AM
4 AM
Time of Testing
= Experimental, Day 1
= Experimental, Day 2
= Control, Day 1
= Control, Day 2

Figure 9. Mean number of errors of commission on the Continuous Performance Task- Visual for the Experimental and Control groups for each time of day on both days.

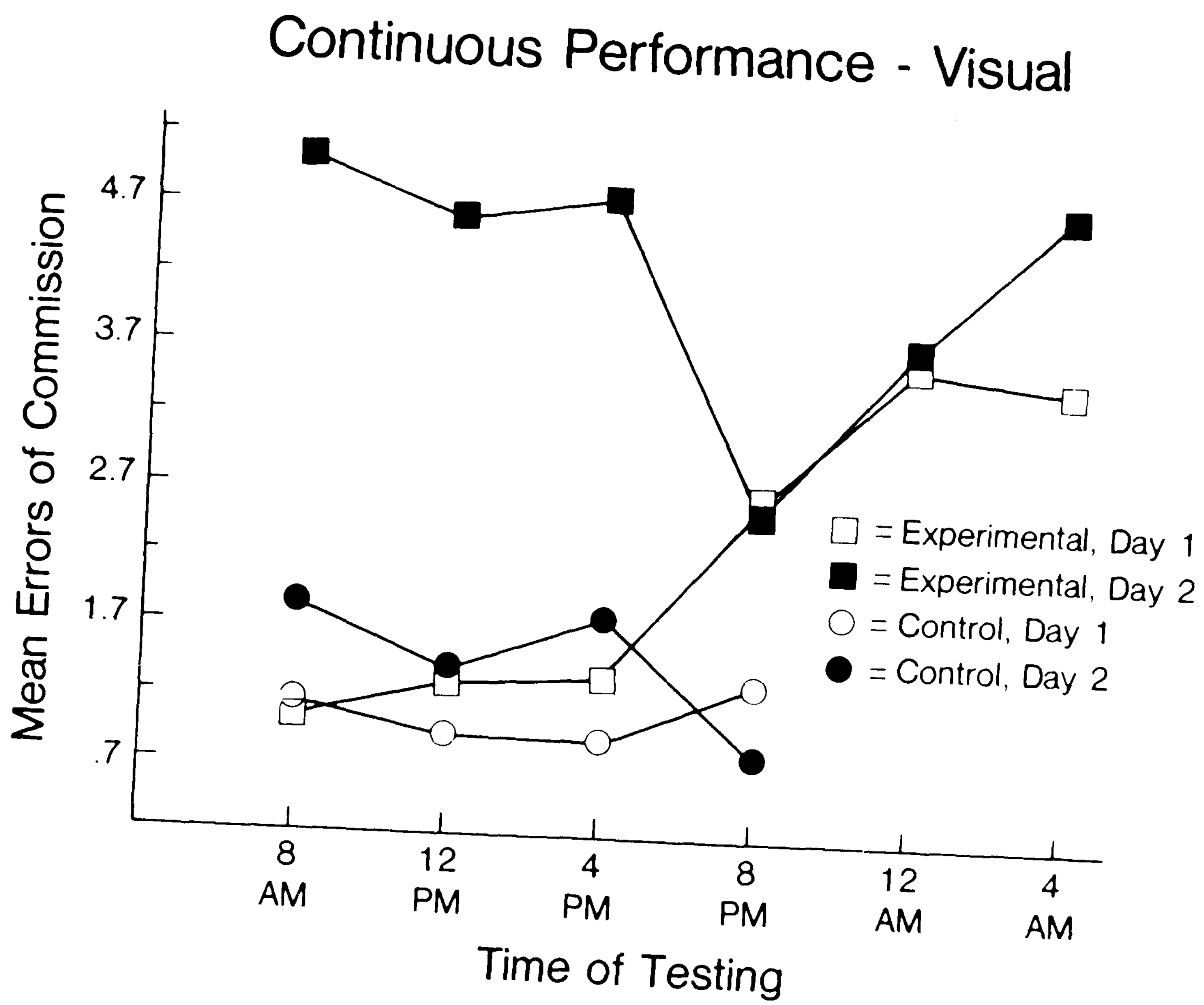
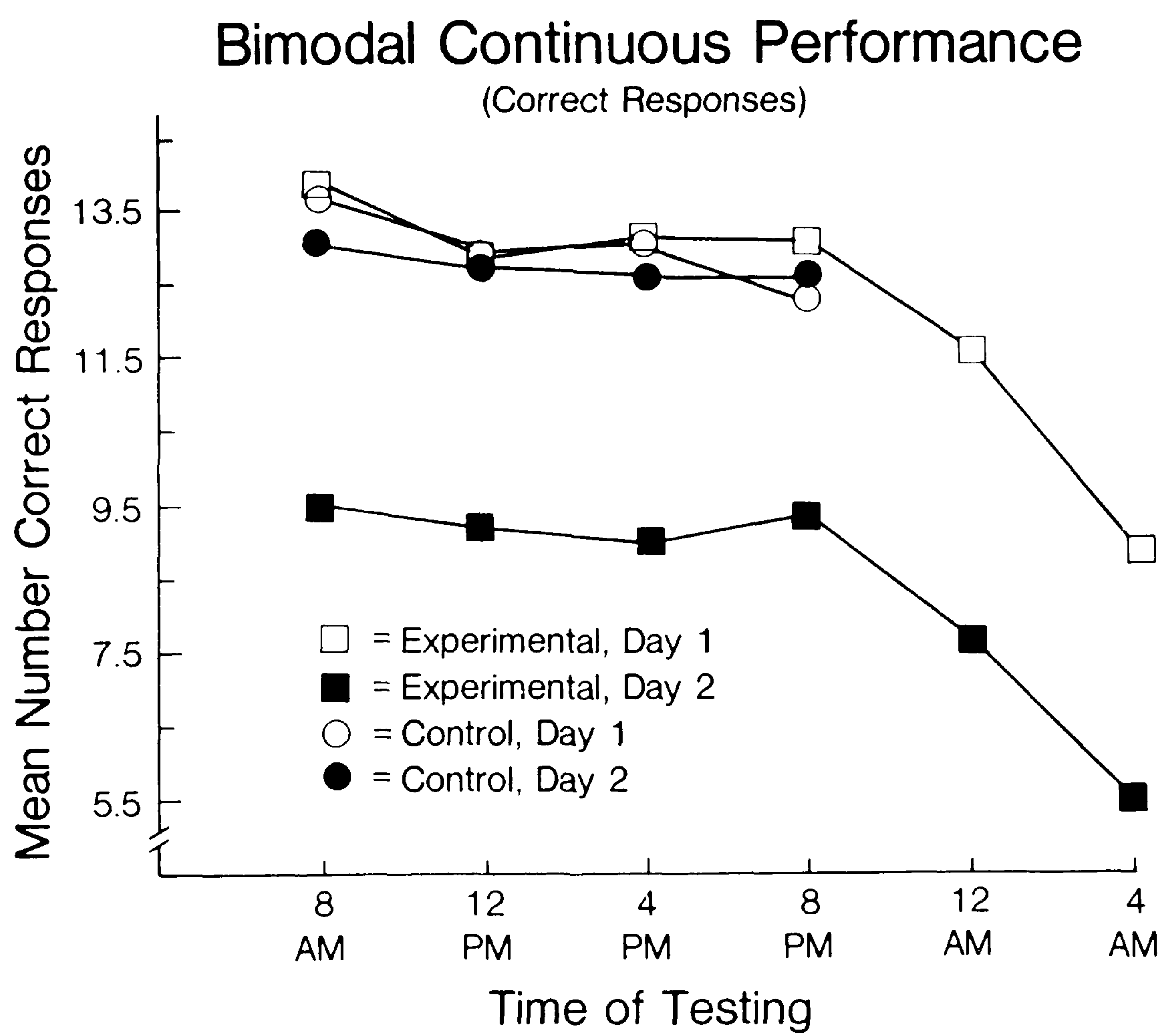

Continuous Performance - Visual
Mean Errors of Commission
4.7
3.7
2.7
1.7
.7
8 AM
12 PM
4 PM
8 PM
12 AM
4 AM
Time of Testing
= Experimental, Day 1
= Experimental, Day 2
= Control, Day 1
= Control, Day 2

Figure 10. Mean number of correct on the Continuous Performance Task-Bimodal for the Experimental and Control groups for each time of day on both days.



Bimodal Continuous Performance
(Correct Responses)
Mean Number Correct Responses
13.5
11.5
9.5
7.5
5.5
= Experimental, Day 1
= Experimental, Day 2
= Control, Day 1
= Control, Day 2
8 AM
12 PM
4 PM
8 PM
12 AM
4 AM
Time of Testing

the visual CPT to the levels of sleep deprivation studied and to the circadian effects observed at Blocks 5 (12 am) and 6 (4 am).

3.4.5 Two-Hand Reaction Time Task

Dependent measures of this task were mean reaction time and mean number of errors. These were derived from fours sets of 25 trials presented at each test session. A Days (1,2) X Blocks (1-6) X Trials (1-4) analysis of variance was used to evaluate the effect of the test conditions on the peformance of the Experimental subjects. A main effect for Days, $F(1/29) = 24.00$, $p < .001$, and Blocks, $F(5,145) = 3.50$, $p < .05$, was obtained. Mean reaction times increased from about .5 ms on the first day to about .7 ms on the second day of deprivation. Examination of the Block effect suggested a circadian influence, i.e., reaction times markedly increased during the night-time test blocks of both days, and tended to recover on the second day in the afternoon and evening hours.

The Experimental and Control group reaction times were compared using a Groups (Experimental, Control) X Days (1,2) X Blocks (1-4) X Trials (1-4) analysis of variance. A Day X Groups interaction effect was obtained, $F(1/38) = 9.20$, $p < .005$. The latter was due to the Experimental group having longer reaction times than the control group on the second but not the first test day.

The same analyses were applied to the mean number of errors committed and similar results were obtained. That is the Experimental group only analysis resulted in a significant Day, $F(1/29) = 20.13$, $p < .001$, and Blocks, $F(5,145) = 3.33$, $p < .05$ effects due to an overall increase in errors on the second day with the rate of increase greater during the night-time tests. The analysis of the Experimental and Control groups together revealed a Group X Day interaction, $F(1/38) = 9.20$, $p < .01$.

3.3 Correspondence Betweeen the ERP and Behaviorral Measures

3.3.1 Across-Block Correlations

The foregoing analyses showed changes in the ERP and performance measures in association with sleep deprivation and time of day. To assess whether the CNS and behavioral measures changed similarly as a function of sleep deprivation and time of day, changes in the 12 block means for the behavioral measures were studied in relation to changes in the 12 block means for each of the ERP components using correlation coefficients (Pearson r).

The results of this analysis are shown in Table 4. Several patterns can be observed in this table. Note that the sign of the coefficient is quite generally negative for the latencies of the different components. This indicates that longer evoked potential latencies are associated with lower levels of performance. The signs for the amplitude measures are mixed, but generally consistent within components across tasks. Higher P3

Table 4. Correlation coefficients describing the relationship between the 12 block means for the ERP components (latency and amplitude) and the 12 block means (% from baseline) for the PAB tasks

ABSOLUTE AMPLITUDES

	P1		N1		P2		N2		P3	
	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T
MATRIX	-.43	-.10	.33	-.16	-.57	-.42	.63	.04	.77	.68
WILK	-.37	-.09	.29	-.08	-.68	-.54	.79	.09	.88	.65
PROBE	-.31	.19	.57	.47	-.29	-.25	.32	.06	.46	.69
SERIAL	-.22	.20	.25	.20	-.48	-.42	.53	-.10	.77	.70
LOGIC	-.19	.29	.30	.34	-.14	-.19	.17	-.16	.37	.63
MAST6	.15	-.07	-.23	.18	.69	.69	-.36	-.51	-.54	-.52

PEAK-TO-PEAK AMPLITUDES

	P1N1		N1P2		P2N2		N2P3	
	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T
MATRIX	-.17	-.13	-.48	-.40	-.28	-.51	.75	.59
WILK	-.11	-.09	-.62	-.45	-.23	-.63	.88	.59
PROBE	.19	.36	-.01	.05	-.16	-.25	.43	.53
SERIAL	-.01	.24	-.42	-.21	-.23	-.66	.72	.53
LOGIC	.11	.36	-.01	.08	-.06	-.32	.32	.39
MAST6	-.07	.01	.63	.57	.89	.33	-.50	-.68

LATENCIES

	P1		N1		P2		N2		P3	
	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T	ERP	ERP/T
MATRIX	-.34	-.27	-.46	-.62	-.82	-.62	-.74	-.86	-.37	-.67
WILK	-.35	-.23	-.45	-.32	-.93	-.61	-.84	-.80	-.37	-.58
PROBE	-.20	-.32	-.36	-.22	-.50	-.46	-.51	-.58	-.30	-.77
SERIAL	-.39	-.40	-.55	-.51	-.87	-.54	-.81	-.86	-.52	-.80
LOGIC	-.29	-.42	-.55	-.51	-.50	-.34	-.46	-.63	-.30	-.83
MAST6	.47	.07	-.30	.17	.50	.75	.64	.46	.50	.24

Note 1: E = ERP only trials, ERP/T = ERP/Tracking trials
Note 2: all underlined values have p < .05 (df = 10)

amplitudes, for example, are associated with higher levels of performance. The opposite seems to be the case for P2 amplitude.

It can also be seen in Table 4, that the statistically significant correlations involve the later components, ie., P2, N2, and P3 as opposed to P1 and N1. Only a small number of significant coefficients is observed for either the latency or amplitude of P1 and N1, or the peak-to-peak amplitude of P1N1.

In an effort to provide a more detailed description of the evoked potential-performance relationship, N2 latency and the throughput measure on the Wilkinson, Matrix, and Serial tasks of the PAB were converted to standard scores and then plotted on the same scale (see Figure 11). The standard score formula was:

$$Z_i = 50 + 10\,(X_i - \overline{X})/s$$

where

Z_i = standard score

X_i = raw score (a Block mean)

$\overline{X}$ = mean of raw scores (mean of Block means)

s = standard deviation ofrawscores(Block means)

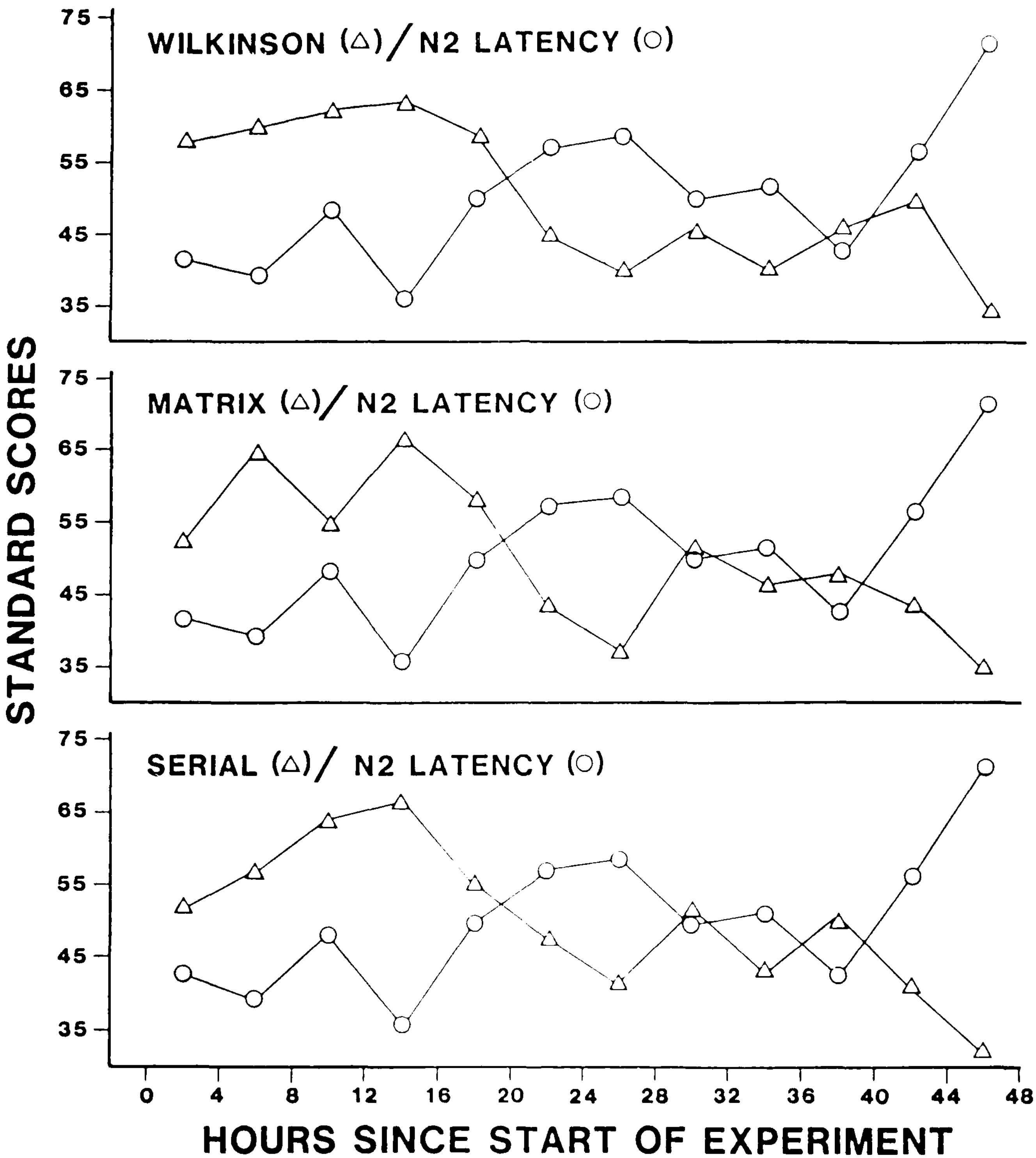
Figure 11 shows quite clearly the extent of correspondence between N2 latency and performance. For all three tasks, it is evident that for this component and this situation, knowledge of changes in this characteristics of the ERP provides considerable knowledge about changes in performance.

3.3.2 Within-Block Correlations

The across-block correlations assessed whether the ERP and behavioral measures varied in some comparable fashion across the testing conditions. To assess whether the characteristics of a subject's evoked potential was related to his performance, additional correlation coefficients were computed for each test block using individual ERP and behavioral scores (PAB throughput measures). Tables 5-8 present the matrices obtained using the amplitude of the P1 component, the peak-to-peak amplitudes of the P1N1 and the N1P2 components, and the latency of the N1 component. Each matrix reveals a similar pattern among the significant coefficients. No patterns were observed in the matrices involving the P2, N2, and P3 components.

It can be seen from the tables, that P1 amplitude, N1 latency, and P1N1 and N1P2 peak-to-peak amplitude, all vary with performance on certain of the tasks on some of the blocks.

Figure 11. N1 latency and throughput measures for the Wilkinson, Matrix, and Serial tasks of the PAB. The scores are expressed as standard scores with a mean of 50 and a standard deviation of 10.



STANDARD SCORES
WILKINSON (△)/ N2 LATENCY (○)
MATRIX (△)/ N2 LATENCY (○)
SERIAL (△)/ N2 LATENCY (○)
75
65
55
45
35
0
4
8
12
16
20
24
28
32
36
40
44
48
HOURS SINCE START OF EXPERIMENT

Table 5. Within-Block correlations between P1 amplitude and PAB throughput measures (% change from baseline)

	LOGICAL		MAST6		MATRIX		PROBE		SERIAL		WILK.	
BLK	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T
1	.27	.45	-.04	.47	.13	.52	.36	.45	-.09	.40	-.19	.27
2	.32	.11	.16	.17	.28	.24	.30	.14	.29	.10	.07	-.02
3	.40	.62	.27	.19	.31	.52	.35	.47	.47	.46	.43	.30
4	.22	.32	.03	.03	.31	.36	.16	.37	.12	.13	.14	.13
5	-.11	.18	.12	.16	-.01	.30	.21	.43	-.18	-.06	.06	-.07
6	.37	.31	.28	.23	.20	.30	.33	.34	.38	.27	.21	.13
7	.11	.14	.09	.23	.40	.43	.47	.31	.27	.34	.18	.08
8	-.11	.02	-.02	.04	.13	.10	-.18	-.06	-.08	-.06	-.03	.04
9	.20	.04	.34	.04	.02	.08	.20	-.00	.15	.08	-.16	-.07
10	.08	.13	.05	-.19	.36	.31	.23	.12	.16	.15	.15	.00
11	.27	-.12	.34	.09	.50	.04	.50	.13	.45	.19	.38	.27
12	.43	-.13	.52	.14	.64	.20	.41	-.08	.32	-.03	.67	.25

Note 1: E = ERP only trials, E/T = ERP/Tracking trials
Note 2: All underlined correlations have p < .05 (df=26)

Table 6. Within-Block correlations between N1 latency and PAB throughput measures (% change from baseline)

	LOGICAL		MAST6		MATRIX		PROBE		SERIAL		WILK.	
BLK	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T
1	.29	.33	.20	.38	.27	.42	.38	.40	.23	.60	.15	.21
2	.25	.27	-.04	.23	.30	.43	.14	.36	.29	.36	.05	.15
3	.15	.33	-.10	.35	.30	.45	.25	.50	.37	.30	-.12	.20
4	.35	.55	.22	.27	.36	.49	.44	.54	.36	.50	.05	.30
5	.26	.34	.18	.34	.34	.62	.35	.52	.19	.33	.13	.07
6	.52	.51	.42	.52	.42	.59	.33	.43	.39	.44	.26	.48
7	.33	.49	.48	.64	.49	.54	.51	.58	.35	.45	-.08	.05
8	-.09	.20	.09	.20	.02	.18	-.03	.21	.07	.36	.05	.02
9	.21	.33	.17	.26	.04	.26	.00	.19	.06	.26	.06	.02
10	.03	.21	.09	.40	.44	.35	.33	.44	.17	.20	-.17	-.09
11	.06	.16	.41	.34	.24	.41	.24	.09	.51	.55	.30	.27
12	.25	.18	.33	.22	.38	.35	.55	.32	.33	.36	.35	.11

Note 1: E = ERP only trials, E/T = ERP/Tracking trials
Note 2: All underlined correlations have p < .05 (df=26)

Table 7. Within-Block correlations between P1N1 amplitude and PAB throughput measures (% change from baseline)

	LOGICAL		MAST6		MATRIX		PROBE		SERIAL		WILK.	
BLK	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T
1	.10	.41	-.01	.45	-.02	.35	.03	.45	-.04	.52	.01	.24
2	.04	.03	-.15	.11	-.07	.01	-.01	-.08	.06	.09	.01	-.03
3	.03	.45	.33	.35	.57	.51	.32	.46	.38	.68	.41	.31
4	.31	.22	.00	.01	.38	.22	.47	.31	.25	.18	.06	.20
5	.06	.15	.16	.27	.08	.44	.27	.52	.08	.19	.09	.27
6	.28	.41	.22	.27	.01	.22	.50	.44	.30	.37	.05	.08
7	.11	.11	-.09	.09	.25	.42	.13	.34	.22	.53	.14	.23
8	-.11	-.04	-.06	-.07	.20	.04	.11	.25	.30	.20	.21	.11
9	-.19	-.21	.06	-.12	.00	.18	.18	.03	.25	.20	-.17	.03
10	-.18	-.16	.00	.02	.07	.04	.35	.21	.12	.09	-.03	-.04
11	.37	-.21	.39	.00	.11	-.41	.65	.08	.41	.10	.22	-.02
12	.42	.21	.11	-.26	.31	-.02	.41	.04	.21	.21	.36	.19

Note 1: E = ERP only trials, E/T = ERP/Tracking trials
Note 2: All underlined correlations have $p < .05$ (df=26)

Table 8. Within-Block correlations between N1P2 amplitude and PAB throughput measures (% change from baseline).

	LOGICAL		MAST6		MATRIX		PROBE		SERIAL		WILK.	
BLK	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T	E	E/T
1	-.40	.19	-.16	-.12	-.41	-.08	-.40	.07	-.34	.26	-.16	.15
2	-.30	-.39	-.31	-.42	-.49	-.50	-.37	-.50	-.31	-.42	-.09	-.27
3	-.49	.02	-.06	.17	.21	.27	.00	.24	-.09	.39	-.07	.18
4	-.11	.00	-.07	-.13	-.07	.16	-.07	.02	-.14	-.19	-.14	-.03
5	-.26	-.33	-.35	-.11	-.47	-.19	-.32	-.31	-.35	-.18	-.19	.05
6	.01	.17	-.09	.08	-.16	.05	.26	.38	.06	.16	-.12	-.16
7	-.25	.05	-.42	-.01	-.35	.23	-.37	.22	-.24	.25	-.10	.28
8	-.13	-.19	-.18	-.11	-.09	-.08	.05	.11	.16	.13	.01	.13
9	-.36	-.33	-.35	-.28	.02	-.14	-.05	-.19	.19	-.02	.01	-.16
10	-.34	-.35	-.22	-.20	-.32	-.26	-.08	-.13	-.09	-.05	-.10	.08
11	.20	-.14	-.13	-.13	-.36	-.61	.16	-.16	-.29	-.27	-.32	-.36
12	.06	.14	-.22	-.12	.00	-.16	.26	.10	-.04	-.04	-.09	-.01

Note 1: E = ERP only trials, E/T = ERP/Tracking trials
Note 2: All underlined correlations have p < .05 (df=26)

Inspection indicates a pattern among the significant correlations which is similar for each matrix and which can be seen most clearly with the N1 latency. For the latter matrix, it can be seen that the large majority of the significant correlations involve the latencies obtained from the ERP/Tracking trials as opposed to the ERP-only trials. This relationship was clearest for the Matrix and Probe tasks. Thus, for these tasks, longer N1 latencies on the ERP/Tracking trials were associated with higher performance.

It can also be seen from Tables 5-8 that the relationship between N1 latency and performance was more evident on some trial blocks than others. For test blocks 6 and 7 (0400 hrs - 1200 hrs; late night of first day and morning of second day) and test blocks 10-12 (2000 hrs - 0800 hrs; evening of the second day through the remainder of the experiment), the relationship was clearer across the PAB tasks than at any other time. As the lowest levels of performance were observed during these test blocks, it is apparent that that the relationship is strongest when performance is most degraded.

It is interesting to note that evoked potential-performance relationships described in Tables 5-8 involve the earlier components of those studied, i.e., P1 and N1, and not the later ones, i.e., P2,N2,P3. Recall that the opposite pattern was found with the across-block correlations.

4.0 DISCUSSION

4.1 Event-Related Brain Potentials (ERPs) and Sleep Loss

Several changes in evoked potentials were observed across the 48-hr testing period of the present experiment. These included decreases in the amplitude of N2, P3, and N2P3 (peak-to-peak); and increases in the amplitudes of P1, P2, and P1N1 (peak-to-peak). Also, there were increases in the latency of P2, N2, and P3. These findings are generally in accordance with the existing literature. Other investigators have found, for example, increased latency and amplitude changes of ERP components in association with sleep loss and/or excessive sleepiness (e.g., Broughton et al., 1982; Gauthier & Gottesmann, 1983; Peeke et al., 1980). The increase in P2 amplitude was somewhat surprising given earlier findings. This may have been due to differences in procedures for eliciting ERPs.

A circadian rhythm was apparent in certain of the ERP components across the 48-hr period. There was a strong tendency for the greatest change to occur during the night-time and morning test blocks on both days. Changes typically in the opposite directions tended to occur during the afternoon and early evening hours.

An important finding of the present study, was that, in general, the evoked potentials obtained while subjects performed the tracking task were more sensitive to the test conditions than the ERPs recorded without the tracking task. That is, as sleep deprivation increased the changes observed with the ERP/Tracking trials tended to parallel more closely the changes observed in performance. Also, the ERPs from ERP/Tracking trials were more closely associated with performance (co-varied) within test blocks. Researchers have shown in other contexts that evoked potential measures are more sensitive to environmental and task manipulations when subjects are concurrently performing two or more tasks (e.g., Kramer et al., 1981). The present findings suggests that a concurrent-task paradigm be used in future studies of the relationship between ERPs and performance degradation.

The present findings also suggest the advisability of using a more extended sleep loss period in future continuous wakefulness studies. That is, for most of the measures, it was apparent from inspection of the data that the greatest changes occurred in the last four to eight hours of the 48-hr test period. Thus, even more dramatic ERP changes and greater ERP/performance correspondence may have been observed if subjects had been deprived of sleep for an additional 24 hours.

It is important to note that although several of the changes observed were unambiguously related to sleep deprivation, not all changes observed in evoked potentials could be attributed to sleep loss. That is, control subjects who were allowed sleep, showed changes across the test conditions which were similar, but smaller, to those seen with experimental subjects. One possible explanation is that control subjects may have experienced some sleep loss due to sleep disruption when awakened for testing purposes. Although these control subjects were permitted to sleep, their sleep was interrupted at 0400 hrs for recording of evoked potentials. The effects of this disrupted sleep may have influenced properties of the evoked potentials. There were no apparent effects of this disruption, however, on the performance of control subjects.

It is also possible that the ERP changes were, in part, due to habituation resulting from repeated testing. For example, although the sleep-deprived subjects had lower N2P3 amplitudes than the control subjects, it was apparent that reductions in amplitudes began on the first day (no sleep loss) for both groups. The possibility of "repeated-testing" effects in the recording of evoked potentials has not received a great deal of attention and future research assessing the effects of environmental, task, or subject variables must address this factor.

4.2 Performance and Sleep Loss

As in many early studies, the present study found that sleep loss resulted in performance degradation. This was evident with all of the tasks used in the present experiment with the exception of the Mast 6 task from the Performance Assessment Battery.

There was also evidence of strong circadian variation in performance across the the two days and nights of the experiment. Generally, performance was lower during the night and morning tests on both Day 1 and Day 2. Also there was a tendency for performance to be higher in the afternoon and early evening tests. We should note that the performance trough occurred during the 4:00 AM testing block. Others have also reported similar findings. It is difficult to attribute the marked performance decrement to any one factor since body temperature, sleepiness, and circadian factors are involved. However, circadian factors are known to influence a variety of measures (see Johnson, 1982, for a review). The important role played by circadian factors was clarified by Rutenfranz et al., (1972). These investigators assessed the relationship among body temperature, performance, and circadian factors. They found a significant correlation in temperature and reaction time across time of day but no relationship between the two, either within subjects or between subjects, when time of day was constant.

There was no clear evidence that any of the tasks were more or less sensitive to sleep deprivation effect. Although the amount of change at a given time period may have been greater for one task than another, the time point at which changes began to appear was typically the same from task to task. (cf. Thorne et al., 1983). Generally, mean changes across test blocks were more orderly and systematic for the Two-Hand Reaction Time task, Short-Term Memory task, and Continuous Performance task (visual, bi-modal) than for the tasks on the Performance Assessment Battery. The throughput measures on the PAB were, however, more closely related to the ERP measures than were the percent correct and error measures from the remaining tasks.

With increases in sleep deprivation subjects occasionally responded indiscriminately and as rapidly as possible to some of the tasks. This occasional pattern was more evident on the PAB than on the other behavioral tasks. It is likely that this behavioral pattern was due to boredom, fatigue, loss of motivation, etc. The consequence was that a true test of functioning was not possible when this behavior emerged and speed and accuracy scores deviated markedly from those of other subjects during the same test block and also deviated from scores for the same subject at other test blocks. This pattern of responding is most apparent when the data are reduced. Strategies for dealing with indiscriminate responding are essential and might include the addition of feedback sessions following each administration of the test battery. In addition, each participant could be encouraged to perform as well as possible prior to beginning each task. It might also be useful to build into the test battery itself a monitoring routine which would automatically detect unusually brief response latencies and provide immediate feedback to subjects via a voice synthesizer.

Some researchers have referred to the "incentive effect" which occurs due to knowledge concerning the end of the continuous wakefulness period (Haslam, 1983). This effect is characterized by moderate to marked improvement in performance and mood as the wakefulness period comes to an end. We did not observe such an effect in the present study but the effect may have been masked by the marked circadian effects observed during the 0400-0800 hrs test block, i.e. the last session, Block 12.

4.3 Effects of Recovery Sleep

The nap data provide information about the restorative value of brief recovery-sleep periods (naps) following extended sleep loss. The observation that the ERP components were markedly reduced following the one-hr nap suggests that a one-hr nap is not restorative and may even be counterproductive. The data trends observed with the two-hr and four-hr naps also suggest that naps of these durations are not fully restorative. However, the ERP values did show signs of recovery at the longer nap durations. In this regard our data are compatible with Morgan (1974) and Haslam (1985). Morgan found that after 36 hrs of continuous work, 12-hrs of sleep was needed for complete recovery (100%) of performance. Complete recovery did not occur with recovery naps of 2, 3, or 4 hrs. Similarly, Haslam found that blocks of 4-hrs of sleep had a beneficial effect on performance but it did not result in complete recovery of performance.

The relationship between nap duration and performance on the behavioral tasks corresponds with the relationship of the naps and evoked potential values. After a one-hr nap, performance was generally below baseline and well below the performance of the control subjects. Some signs of recovery began at 2 and 4 hrs.

A note of caution should be sounded regarding the above relationships involving recovery sleep. Circadian factors may have played a role in determining the pattern. Test sessions following naps of different durations were unavoidably conducted at different times of the day. Control subjects were tested at around 0800 hrs and the four-hr nap subjects were tested at about 1300 hrs. Therefore the obtained differences differences, could have been a function of time of day. Another factor that is difficult to assess and is often ignored in recovery sleep studies is the effect of prior sleep on various recorded measures. There is considerable evidence that both the duration and stage of prior sleep can have marked effects on performance for some time after awakening. These effects are much more pronounced for cognitive tasks than for physical tasks. The phenomena is usually referred to as the "sleep inertia effect" (Dinges, Orne, & Orne, 1985). The latter investigators found that sleep inertia following naps near the temperature trough (early morning) was far more severe than naps near the temperature peaks. Naitoh (1981) also reported that sleep inertia following naps between 0400-0600 hours was severe and long lasting. No beneficial effects of naps at these hours were seen for 2 to 6 hrs. This was not the case for naps occurring between 1200-1400 hrs, even after 53 hours of continuous wakefulness. Sleep inertia effects due to naps can also be seen in the findings of Mullaney, Kripke, Fleck, and Johnson (1983).

4.4 Correspondence Between ERPs and Performance

The systematic correpondence between certain ERP components and performance measures may hold great promise for predicting performance degradation. Several interesting relationships obtained. The relationships of most interest include 1) the high correlation between changes in mean performance values across the 12 four-hour blocks and changes in mean amplitudes and latencies of certain of the evoked potentials across the 12 blocks, and 2) the high correlation between subject differences in ERP values and their differences in performance within the same test block.

Finding that the changes in performance across the 12 test blocks were related to changes in evoked potentials across the test blocks (i.e. both co-vary with sleep deprivation) suggest that knowledge of evoked potentials can be used to make predictions about performance. For example it was found that during the 48-hr test period, relatively long N2 latencies, whether due to sleep deprivation, circadian rhythms, or other factors, could be used to predict relatively low performance. The findings regarding the N2 component were surprising. This component of the wave form appeared to be a better predictor of performance than did P3. Others have also investigated the relationship of the N2 component to the P3 component (Michalewski, Prasher, & Starr, 1986). These researchers found a strong co-varying relationship between N2 and P3 components with N2 accounting for 61% of the variance of the P3 latency. They also report that the highest correlation between peak latency and reaction time was found for N2, the next highest was P3.

The evoked response-performance relationship should be interpreted cautiously. It is possible that the correspondence between the two variables is due to their mutual relationship with some third variable, e.g. body temperature. The latter would not alter the predictive value of the ERPs but it is possible that other factors which degrade behavior (excessive heat or cold, chemical agents) may not systematically affect ERP measure. It is obviously important that relationships between ERPs, behavior and other performance degradation conditions be explored.

Another concern is that the relationships noted between evoked responses and performance may obtain for only certain types of behaviors. In the present experiment the throughput measures on the PAB (rate of correct responding) were related to evoked potentials but the relationship with other variables (e.g.,% correct, errors of omission, errors of commission) and other tasks was not as clear. This may have been due to evoked potentials being associated only with subjects' ability to maintain a steady level of correct responding and not to other performance dimensions such as probability or simple rate of responding.

The evoked potentials- performance relationship within test blocks suggests the interesting possibility that ERPs can be used to classify subjects as good and poor performers. Previous research has suggested that ERP characteristics distinguish between groups on a variety of dimensions including the presence or absence of absolute pitch (Klein et al., 1984), children of alcoholic and non-alcoholic fathers (Begleiter et al, 1984), and successful and unsuccessful Navy recruits (Lewis et al., 1982). There are few studies, however on the relationship between ERP characteristics and normal intersubject variation in psychomotor performance.

Although the within block correlations between ERP components and performance were found more (i.e. with more tasks) during the early morning test blocks, there was evidence of a similar relationship on the very first test block. The latter suggests the possibility of predicting which subjects would show the least and which would show the greatest levels of change to sleep deprivation on the subsequent test blocks. The obvious value of this predictive information warrants further study.

While the relationships observed in the present study appear to hold considerable promise for predicting behavior, it is clear that additional research is needed. It is necessary to determine the replicability of the findings and to assess the limits of their generalizability.

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APPENDIX 1

ABSOLUTE AMPLITUDE CHANGES ACROSS DAYS AND BLOCKS FOR ERP COMPONENTS

P1 Amplitude (ERP only)

		1	2	3	4	5	6
DAY 1: EXP:	$\bar{X}$	1.75	2.18	2.48	2.49	1.69	2.53
	s.d.	1.14	1.04	1.20	1.68	2.07	1.56
CONTROL:	$\bar{X}$	1.88	2.65	2.52	2.42	-	2.45
	s.d.	1.89	1.64	1.31	1.14	-	1.64
DAY 2: EXP:	$\bar{X}$	2.94	2.13	2.05	2.23	2.28	2.55
	s.d.	1.40	1.90	1.21	1.61	1.33	1.28
CONTROL:	$\bar{X}$	2.48	1.86	3.16	2.50	-	1.97
	s.d.	1.52	0.95	1.04	0.94	-	1.52

P1 AMP (ERP/T)

		1	2	3	4	5	6
DAY 1 EXP:	$\bar{X}$	1.61	1.88	2.31	2.30	1.64	2.36
	s.d.	0.95	1.49	1.15	1.01	1.38	1.06
CONTROL:	$\bar{X}$	1.97	1.85	2.25	2.70	-	1.95
	s.d	1.49	0.78	1.47	1.35	-	1.43
DAY 2 EXP:	$\bar{X}$	2.40	1.88	1.92	2.02	1.73	1.88
	s.d.	1.10	0.93	0.94	0.75	0.76	0.87
CONTROL:	$\bar{X}$	2.52	1.70	2.22	3.07	-	1.38
	s.d.	1.24	1.22	1.20	0.79	-	0.45

P2 Amplitude (ERP only)

		1	2	3	4	5	6
DAY 1: EXP:	X̄	.52	1.15	1.57	1.70	1.52	2.09
	s.d.	1.45	1.28	1.61	1.68	1.00	1.39
CONTROL:	X̄	1.93	2.03	2.55	1.20	-	1.20
	s.d	1.33	2.23	1.46	2.08	-	1.55
DAY 2: EXP:	X̄	1.84	1.85	1.86	2.14	1.91	2.40
	s.d.	1.37	1.46	1.44	1.55	1.37	.74
CONTROL:	X̄	2.45	2.56	2.47	2.42	-	1.88
	s.d.	1.20	1.50	2.06	1.13	-	1.46

P2 AMP (ERP/T)

		1	2	3	4	5	6
DAY 1 EXP:	X̄	0.59	0.79	1.29	1.20	1.10	1.10
	s.d.	0.89	1.15	1.06	1.29	1.22	1.59
CONTROL:	X̄	1.56	1.27	1.18	1.45	-	0.78
	s.d.	1.35	1.35	1.00	1.36	-	1.59
DAY 2 EXP:	X̄	1.08	1.58	1.51	1.07	1.43	1.73
	s.d.	1.21	1.02	1.47	1.34	0.84	1.26
CONTROL:	X̄	1.93	1.82	1.72	2.18	-	1.41
	s.d.	1.22	1.21	1.34	0.67	-	0.62

N2 Amplitude (ERP only)

		1	2	3	4	5	6
DAY 1 EXP:	$\overline{X}$	2.55	2.06	1.99	1.89	1.89	1.37
	s.d.	1.93	1.88	1.53	1.59	1.61	1.21
CONTROL:	$\overline{X}$	2.33	2.47	2.43	2.04	-	2.01
	s.d.	2.37	2.20	1.66	1.60	-	1.62
DAY 2 EXP:	$\overline{X}$	1.30	1.65	1.61	1.43	1.96	1.29
	s.d.	1.07	1.42	1.35	1.48	1.51	1.05
CONTROL:	$\overline{X}$	1.76	1.56	1.22	0.93	-	1.49
	s.d.	1.62	1.40	1.34	1.48	-	1.31

N2 AMP (ERP/T)

		1	2	3	4	5	6
DAY 1 EXP:	$\overline{X}$	1.99	1.94	2.53	2.12	2.15	2.47
	s.d.	1.20	1.22	1.32	1.32	1.28	1.55
CONTROL:	$\overline{X}$	1.54	2.03	2.40	1.60	-	1.76
	s.d.	1.46	1.49	1.78	1.62	-	0.94
DAY 2 EXP:	$\overline{X}$	2.29	2.58	2.05	2.40	2.22	2.00
	s.d.	1.28	1.09	1.31	1.57	1.04	1.40
CONTROL:	$\overline{X}$	1.13	1.81	1.75	1.02	-	2.42
	s.d.	1.63	1.14	1.53	1.08	-	1.13

N1P2 Amplitude (ERP only)

		1	2	3	4	5	6
DAY 1 EXP:	X̄	2.45	3.14	3.41	3.09	3.36	3.83
	s.d.	1.25	1.71	2.02	1.73	1.57	1.70
CONTROL:	X̄	3.41	3.84	3.46	2.91	-	2.75
	s.d.	1.70	2.20	1.79	1.32	-	.77
DAY 2 EXP:	X̄	3.38	3.61	3.95	3.77	3.66	3.61
	s.d.	1.84	1.70	1.98	1.89	1.63	1.55
CONTROL:	X̄	3.75	3.41	2.82	4.07	-	3.18
	s.d.	1.54	1.73	2.63	1.77	-	1.73

N1P2 Amplitude (ERP/T)

		1	2	3	4	5	6
DAY 1 EXP:	X̄	2.63	2.79	3.82	3.32	3.25	3.57
	s.d.	1.16	1.30	1.70	1.70	1.25	1.80
CONTROL:	X̄	3.09	3.30	3.57	3.05	-	2.54
	s.d.	1.25	.95	1.39	1.71	-	1.66
DAY 2 EXP:	X̄	3.38	4.16	3.59	3.48	3.64	3.73
	s.d.	1.34	1.02	2.18	1.80	1.34	1.54
CONTROL:	X̄	3.05	3.63	3.46	3.20	-	3.84
	s.d.	1.16	1.64	1.93	1.45	-	1.46

P3 Amplitude (ERP/T)

		1	2	3	4	5	6
DAY 1							
EXP:	$\bar{X}$	2.45	3.14	3.41	3.09	3.36	3.83
	s.d.	1.25	1.71	2.02	1.73	1.57	1.70
CONTROL:	$\bar{X}$	3.41	3.84	3.46	2.91	-	2.75
	s.d.	1.70	2.20	1.79	1.32	-	.77
DAY 2							
EXP:	$\bar{X}$	3.38	3.61	3.95	3.77	3.66	3.61
	s.d.	1.84	1.70	1.98	1.89	1.63	1.55
CONTROL:	$\bar{X}$	3.75	3.41	2.82	4.07	-	3.18
	s.d.	1.54	1.73	2.63	1.77	-	1.73

N1P2 Amplitude (ERP/T)

		1	2	3	4	5	6
DAY 1							
EXP:	$\bar{X}$	2.63	2.79	3.82	3.32	3.25	3.57
	s.d.	1.16	1.30	1.70	1.70	1.25	1.80
CONTROL:	$\bar{X}$	3.09	3.30	3.57	3.05	-	2.54
	s.d.	1.25	0.95	1.39	1.71	-	1.66
DAY 2							
EXP:	$\bar{X}$	3.38	4.16	3.59	3.48	3.64	3.73
	s.d.	1.34	1.02	2.18	1.80	1.34	1.54
CONTROL:	$\bar{X}$	3.05	3.63	3.46	3.20	-	3.84
	s.d.	1.16	1.64	1.93	1.45	-	1.46

P3 Amplitude (E & H)

		1	2	3	4	5	6
DAY 1 EXP:	$\bar{X}$	2.84	2.13	2.27	2.63	2.04	2.16
	s.d.	1.82	1.86	1.30	1.64	1.45	0.98
CONTROL:	$\bar{X}$	2.41	2.52	2.18	1.80	-	2.16
	s.d.	1.50	1.41	1.16	1.13	-	0.75
DAY 2 EXP:	$\bar{X}$	1.54	1.89	2.39	1.75	1.46	1.05
	s.d.	1.09	1.27	1.38	1.20	1.00	1.68
CONTROL:	$\bar{X}$	1.80	1.73	2.86	1.93	-	1.68
	s.d.	1.39	1.59	1.61	0.73	-	0.84

N2P3 Amplitude (E & H)

		1	2	3	4	5	6
DAY 1 EXP:	$\bar{X}$	5.09	4.18	3.55	3.98	3.84	3.86
	s.d.	2.46	1.86	1.50	2.38	1.98	1.64
CONTROL:	$\bar{X}$	3.96	4.00	4.20	3.88	-	3.61
	s.d.	2.00	1.54	1.57	1.84	-	1.30
DAY 2 EXP:	$\bar{X}$	3.34	3.68	3.84	3.39	3.16	2.61
	s.d.	1.71	1.77	1.66	1.64	1.23	1.71
CONTROL:	$\bar{X}$	2.61	3.41	4.05	2.38	-	3.39
	s.d.	1.09	1.46	1.82	0.98	-	1.34